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# THE ELECTRICAL RESISTIVITY LOG AS AN AID IN DETERMINING SOME RESERVOIR CHARACTERISTICS

# The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics

By G. E. Archie*

(Dallas Meeting, October 1941)

The usefulness of the electrical resistivity log in determining reservoir characteristics is governed largely by: (1) the accuracy with which the true resistivity of the formation can be determined; (2) the scope of detailed data concerning the relation of resistivity measurements to formation characteristics; (3) the available information concerning the conductivity of connate or formation waters; (4) the extent of geologic knowledge regarding probable changes in facies within given horizons, both vertically and laterally, particularly in relation to the resultant effect on the electrical properties of the reservoir. Simple examples are given in the following pages to illustrate the use of resistivity logs in the solution of some problems dealing with oil and gas reservoirs. From the available information, it is apparent that much care must be exercised in applying to more complicated cases the methods suggested. It should be remembered that the equations given are not precise and represent only approximate relationships. It is believed, however, that under favorable conditions their application falls within useful limits of accuracy.

## Introduction

The electrical log has been used extensively in a qualitative way to correlate formations penetrated by the drill in the exploitation of oil and gas reservoirs and to provide some indication of reservoir content. However, its use in a quantitative way has been limited because of various factors that tend to obscure the significance of the electrical readings obtained. Some of these factors are the borehole size, the resistivity of the mud in the borehole, the effect of invasion of the mud filtrate into the formation, the relation of the recorded thickness of beds to electrode spacing, the heterogeneity of geologic formations, the salinity or conductivity of connate water, and, perhaps of greatest importance, the lack of data indicating the relationship of the resistivity of a formation *in situ* to its character and fluid content.

On the Gulf Coast it is found that the effects of the size of the borehole and the mud resistivity are generally of little importance, except when dealing with high formational resistivities or extremely low mud resistivities. Fortunately, little practical significance need be attached to the exact values of the higher resistivities recorded. Low mud resistivities are not common, but when this condition is encountered it may be corrected by replacing the mud column. With the present advanced knowledge of mud control, invasion of mud filtrate into sands can be minimized, thereby increasing the dependability of the electrical log. The effect of electrode spacing on the recorded thickness of a bed is often subject to compensation or can be sufficiently accounted for to provide an acceptable approximation of the true resistivity of the formation. As development of a field or area progressively enhances the knowledge of the lithologic section, the resistivity values of the electrical log take on greater significance, ultimately affording acceptable interpretations. The salinity, and

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therefore the conductivity, of the connate water associated with the various producing horizons may be determined with sufficient accuracy by the usual sampling procedure.

Determination of the significance of the resistivity of a producing formation as recorded by the electrical log appears, for the present at least, to rest largely with the application of empirical relationships established in the laboratory between certain of the physical properties of a reservoir rock and what may be termed a formation factor. It should be stressed at this point that numerous detailed laboratory studies of the physical properties of the formations in relation to the electrical measurements in question are essential to a reliable solution of the problems dealing with reservoir content. The purpose of this paper is to present some of these laboratory data and to suggest their application to quantitative studies of the electrical log. It is not intended to attempt to discuss individual resistivity curves and their application. The disturbing factors (borehole, bed thickness, and invasion) are discussed briefly only to indicate instances when they are not likely to affect the usefulness of the observed resistivity.

## Resistivity of Sands when Pores Are Entirely Filled with Brine

A study of the resistivity of formations when all the pores are filled with water is of basic importance in the detection of oil or gas by the use of an electrical log. Unless this value is known, the added resistivity due to oil or gas in a formation cannot be determined.

The resistivities of a large number of brine-saturated cores from various sand formations were determined in the laboratory; the porosity of the samples ranged from 10 to 40 per cent. The salinity of the electrolyte filling the pores ranged from 20,000 to 100,000 milligrams of NaCl per liter. The following simple relation was found to exist for that range of porosities and salinities:

$$R_o = FR_w \qquad [1]$$

where $R_o$ = resistivity of the sand when all the pores were filled with brine, $R_w$ = resistivity of the brine, and $F$ = a "formation resistivity factor."

In Figs. 1 and 2, $F$ is plotted against the permeabilities and porosities, respectively, of the samples investigated. The data presented in Fig. 1 were obtained from consolidated sandstone cores in which the cementing medium consisted of various amounts of calcareous as well as siliceous materials. The cores had essentially the same permeability, parallel to and perpendicular to the bedding of the layers. All of the cores were from producing zones in the Gulf Coast region. Cores from the following fields were used: Southeast Premont, Tom Graham, Big Dome-Hardin, Magnet-Withers, and Sheridan, Texas; also La Pice, and Happytown, La. Fig. 2 presents similar data obtained from cores of a widely different sandstone; that is, one that had extremely low permeability values compared with those shown in Fig. 1 for corresponding porosities. These cores were from the Nacatoch sand in the Bellevue area, Louisiana.

From Figs. 1 and 2 it appears that the formation resistivity factor $F$ is a function of the type and character of the formation, and varies, among other properties, with the porosity and permeability of the reservoir rock; many points depart from the average line shown, which represents a reasonable relationship. Therefore, individual determinations from any particular core sample may deviate considerably from the average. This is particularly true for the indicated relationship to permeability. Further, although the variation of $F$ with porosity for the two groups of data taken from sands of widely different character is quite consistent, the effect of variations in permeability on this factor is not so evident. Naturally the two relationships could not be held to apply with equal rigor because of the well established fact that permeability does not bear the same relation to porosity in all sands. From close inspection of these data, and at the present stage of the investigation, it would appear reasonably accurate to accept the indicated relationship between the formation resistivity factor and porosity. Thus, knowing the porosity of the sand in question, a fair estimate may be made of the proper value to be assigned to $F$, based upon the indicated empirical relationship

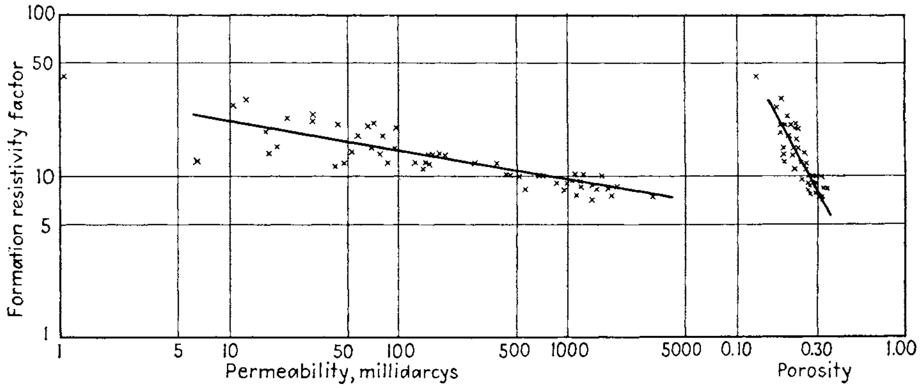


FIG. 1.—RELATION OF POROSITY AND PERMEABILITY TO FORMATION RESISTIVITY FACTOR FOR CONSOLIDATED SANDSTONE CORES OF THE GULF COAST.

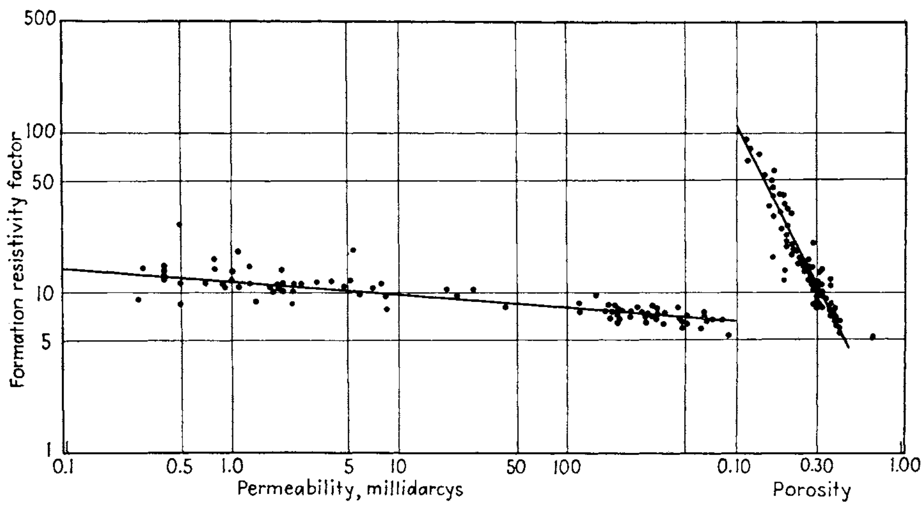


FIG. 2.—RELATION OF POROSITY AND PERMEABILITY TO FORMATION RESISTIVITY FACTOR, NACATOCH SAND, BELLEVUE, LA.

Permeabilities below 0.1 millidarcy not recorded.

$$F = \theta^{-m} \qquad [2]$$

or from Eq. 1,

$$R_o = R_w\theta^{-m} \qquad [3]$$

where $\theta$ is the porosity fraction of the sand and $m$ is the slope of the line representing the relationship under discussion.

From a study of many groups of data, $m$ has been found to range between 1.8 and 2.0 for consolidated sandstones. For clean unconsolidated sands packed in the laboratory, the value of $m$ appears to be about 1.3. It may be expected, then, that the loosely or partly consolidated sands of the Gulf Coast might have a value of $m$ anywhere between 1.3 and 2.

## Resistivity of Formations when Pores Are Partly Filled with Brine, the Remaining Voids Being Filled with Oil or Gas

Various investigators—Martin,[1] Jakosky,[2] Wyckoff,[3] and Leverett[4]—have studied the variation in the resistivity of sands due to the percentage of water contained in the pores. This was done by displacing varying amounts of conducting water from the water-saturated sand with nonconducting fluid. Fig. 3 shows the relation which the various investigators found to exist between $S$ (fraction of the voids filled with water) and $R$ (the resulting resistivity of the sand) plotted on logarithmic coordinates. For water saturations down to about 0.15 or 0.20, the following approximate equation applies:

$$S = \left(\frac{R_o}{R}\right)^{\frac{1}{n}} \quad \text{or} \quad R = R_o S^{-n} \qquad [4]$$

For clean unconsolidated sand and for consolidated sands, the value of $n$ appears to be close to 2, so an approximate relation can be written:

$$S = \sqrt{\frac{R_o}{R}} \qquad [5]$$

or from Eq. 1,

$$S = \sqrt{\frac{FR_w}{R}} \qquad [6]$$

Since in the laboratory extremely short intervals of time were allowed for the establishment of the equilibrium conditions compared with underground reservoirs, there is a possibility that the manner in which the oil or gas is distributed in the pores may be so different that these relations derived in the laboratory might not apply underground.

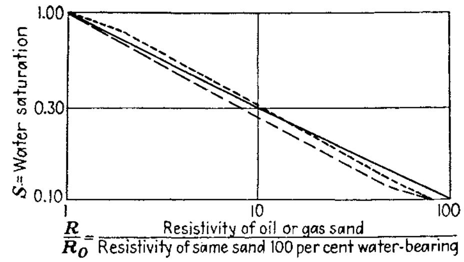


FIG. 3.—Relation of $S$ to $\frac{R}{R_o}$

*Legend and Data*

| Curve | Investigator | Type Sand | Salinity of Water, Grams NaCl per Liter | Oil or Gas | Porosity Fraction |
|---|---|---|---|---|---|
| ——— | Wyckoff | Various | | $CO_2$ | Various |
| ——— | Leverett | Uncons. | 8 approx. | Oil | 0.40 |
| – – – | Martin | Cores | 130 | Oil | 0.20 and 0.45(?) |
| ------ | Jakosky | Friable | 29 approx. | Oil | 0.23 |

Considerable encouragement on this point is established, however. For example, Eq. 4 appears to hold even though gas or oil is the nonconducting phase. Each probably assumes a different distribution in the pores, yet the resulting resistivity is not appreciably changed. Also, no great change is found in the average relation between the formation resistivity factor and porosity for changes in types of consolidated sandstones. This indicates that even though the oil or gas underground may fill the pore space in a different manner from that in the short-time laboratory experiments, the relationship expressed by Eq. 4 should apply equally well underground.

## Basic Resistivity Values to Be Obtained in Estimating Fluid Content of a Sand

The foregoing discussion indicates that the basic values to be obtained are: (1) the resistivity of the sand in question under-

[1] References are at the end of the paper.

ground ($R$), and (2) the resistivity of the same sand when its pores are entirely filled with connate water ($R_o$).

The first value can be obtained from the electrical log when all factors can be properly weighed. The latter may also be obtained from the log when a log is available on the same horizon where it is entirely water-bearing. Of course, this is true only when the sand conditions, particularly porosity, are the same as at the point in question and when the salinity of the connate or formation water throughout the horizon is the same.

In a water-drive reservoir, or any reservoir where the connate water is in direct contact with the bottom or edge water, there should be no appreciable difference in the salinities through the horizon, at least within the limits set forth for the operation of Eqs. 1 and 4; that is, when the salinity of the connate water is over 20,000 mg. NaCl per liter and the connate water is over 0.15. In depletion-type reservoirs, or when connate water is not in direct contact with bottom or edge water, special means may have to be devised to ascertain the salinity of the connate water.

When it is not possible to obtain $R_o$ in the manner described above, the value can be approximated from Eq. 3, $\theta$ and $m$ having been determined by core analyses and $R_w$ by regular analyses.

## Calculation of Connate Water, Porosity and Salinity of Formation Water from the Electrical Log

The resistivity scale used by the electrical logging companies is calculated assuming the electrodes to be points in a homogeneous bed.[5] Therefore, the values recorded must be corrected for the presence of the borehole, thickness of the layers in relation to the electrode spacing, and any other condition different from the ideal assumptions used in calculating the scale.

Consider a borehole penetrating a large homogeneous layer, in which case the electrode spacing is small in comparison with the thickness of the layer. If the resistivity of the mud in the hole is the same as the resistivity of the layer, there will be, of course, no correction for the effect of the borehole. If the resistivity of the mud differs from the resistivity of the layer, there will be a correction. Table 1 shows approximately how the presence of the borehole changes the observed resistivity for various conditions. The third curve, or long normal, of the Gulf Coast is considered because this arrangement of electrodes gives very nearly a symmetrical picture on passing a resistive layer and has sufficient penetration in most instances to be little affected by invasion when the filtrate properties of the mud are suitable.

TABLE 1.—*Effect of Borehole on Infinitely Large Homogeneous Formation*

| True Resistivity of Formation, Meter-ohms | Observed Resistivity on Electric Log | | | |
|---|---|---|---|---|
| | In an 8-in. Borehole | | In a 15-in. Borehole | |
| | Resistivity of Mud in Hole (at Bottom-hole Temperature) of | | Resistivity of Mud in Hole (at Bottom-hole Temperature) of | |
| | 0.5 Meter-ohms | 1.5 Meter-ohms | 0.5 Meter-ohms | 1.5 Meter-ohms |
| 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 1 | 1 | 1 | 1 | 1 |
| 5 | 6 | 5 | 5 | 5 |
| 10 | 12 | 11 | 11 | 11 |
| 50 | 65 | 65 | 50 | 55 |

The values in Table 1 have been calculated assuming a point potential "pick-up" electrode 3 ft. away from a point source of current, other electrodes assumed to be at infinity, and it has been found that the table checks reasonably well with field observations. Checks were made by: (1) measuring the resistivity of shale and other cores whose fluid content does not change during the coring operation and extraction from the well; (2) measuring the resistivity of porous cores from water-bearing formations after these cores were resaturated with the original formation water. Adjustment due to temperature difference, of course, is necessary before the laboratory measurement is compared with the field measurement.

TABLE 2.—*Effect of Formation Thickness, No Borehole Present*

| True Resistivity | Observed Resistivity | | |
|---|---|---|---|
| Layer between Large Shale Bodies Having Resistivity of 1.0 Meter-ohms | Thickness of Layer | | |
| | 24 Ft. | 16 Ft. | 8 Ft. |
| 1 | 1 | 1 | 1 |
| 5 | 5 | 5 | 3 |
| 10 | 10 | 9 | 6 |
| 20 | 20 | 19 | 11 |

The correction at the higher resistivities appears to be appreciable. However, in the Gulf Coast when the value of $R_o$ is low the correction is not so important. For example, assume a friable oil sand whose true resistivity is 50 meter-ohms and whose resistivity when entirely water-bearing is 0.50 meter-ohms; the connate water would occupy about 0.10 of the pore volume (Eq. 5). However, if the observed value on the log, 65 meter-ohms, were used without correcting for the borehole, the connate water would be calculated to occupy 0.09 of the pore volume. Therefore, although the effect of the borehole size and mud resistivity on the observed resistivity readings may be appreciable, the resultant effect on the calculated connate-water content of the sand is not important.

When the thickness of the formation is very large in comparison with the electrode spacing, there will, of course, be no correction to make for the thickness of the layer. However, when the thickness of the formation approaches the electrode spacing, the observed resistivity may be very different from the true value. Table 2 shows approximately what the third curve (long normal) of the Gulf Coast would read for certain bed thicknesses and resistivities. It is assumed that large shale bodies are present above and below the beds, at the same time neglecting the presence of the borehole and again assuming point electrodes.

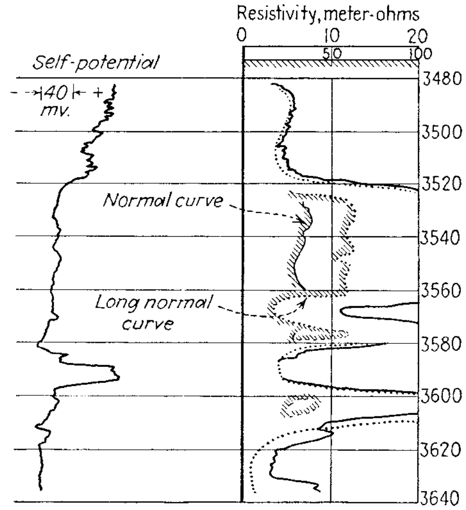


FIG. 4.—ELECTRICAL LOG OF AN EAST TEXAS WELL.
Diameter of hole, 7⅞ in.; mud resistivity, 3.4 at 85°F.; bottom-hole temperature, approximately 135°F.

Tables 1 and 2 assume ideal conditions, so if the sand is not uniform, or if invasion affects the third curve, the observed resistivity values may deviate farther from the true value. The magnitude of the influencing factors, of course, will limit the usefulness of the observed resistivity value recorded on the log. Invasion of the mud filtrate is probably the most serious factor; however, as previously mentioned, it can often be controlled by conditioning the mud flush for low filtrate loss.

Fig. 4 shows a log of an East Texas well. The observed resistivity on the long normal curve for the interval 3530 to 3560 ft. is 62 meter-ohms, or, from Table 1, approximately 50 meter-ohms after correcting for the borehole. In this instance the mud resistivity at the bottom-hole temperature of 135°F. is approximately 2.2 meter-ohms.

The interval is thick enough so that there should be no appreciable effect due to electrode spacing. The formation is more or less a clean friable sandstone, so Eq. 5 can

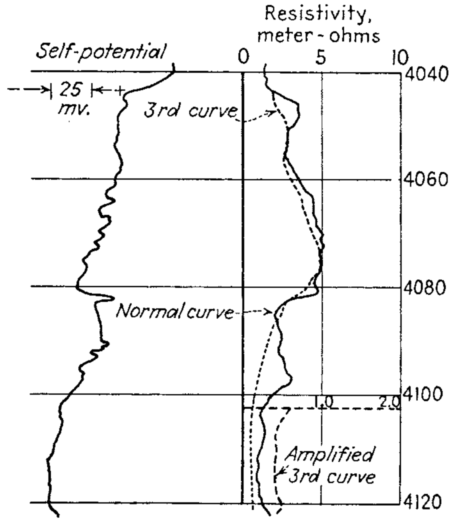


FIG. 5.—ELECTRICAL LOG OF A SAND IN EAST WHITE POINT FIELD, TEXAS.
Diameter of hole, 7⅞ in.; mud resistivity, 1.7 at 80°F.; bottom-hole temperature, 138°F.

be used to approximate the connate-water content. The formation resistivity factor for this sand is approximately 15, using Eq. 2 where $\theta = 0.25$ and $m = 1.8$. The resistivity of the formation water by actual measurement is 0.075 meter-ohms at a bottom-hole temperature of 135°F. Therefore, from Eq. 1, $R_o$ for this sand is $15 \times 0.075 = 1.1$ meter-ohms. This value checks reasonably well with the value recorded at 3623 to 3638 ft. on this log as well as on the many logs from this pool where the Woodbine sand is water-bearing; i.e., 0.9 to 1.5 meter-ohms. The close check obtained between the calculated and recorded resistivity of the water sand indicates that invasion is not seriously affecting the third curve. Solving Eq. 5, the connate water of the zone 3530 to 3560 ft. occupies approximately $\sqrt{\frac{1.1}{50}} = 0.15$ of the pore volume. The accepted value assigned for the connate-water content of the East Texas reservoir is 17 per cent.

An electrical log of a sand in the East White Point field, Texas, is shown in Fig. 5. The observed resistivity at 4075 ft. is approximately 5 meter-ohms. The value of $F$ for this sand by laboratory determination is 6. The sand is loosely consolidated, having 32 per cent porosity average. The resistivity of the formation water by direct measurement is 0.063 meter-ohms at the bottom-hole temperature of 138°F. Therefore, $R_o = 6 \times 0.063$ or 0.38 meter-ohms. This checks well with the value obtained by the electrical log between the depths of 4100 and 4120 ft., which is 0.40 (see amplified third curve). Therefore, invasion probably is not seriously affecting the third curve. From Tables 1 and 2 it appears that the borehole and electrode spacing do not seriously affect the observed resistivity at 4075 ft. The connate water is approximately $\sqrt{\frac{0.38}{5.0}}$, or 0.27.

Other uses of the empirical relations may have occurred to the reader. One would be the possibility of approximating the maximum resistivity that the invaded zone could reach (when formation water has a greater salinity than borehole mud) by Eq. 1, where $R_w$ would now be the resistivity of the mud filtrate at the temperature of the formation and $F$ the resistivity factor of the formation near the borehole. By knowing the maximum value of resistivity that the invaded zone could reach, the limits of usefulness of the log could be better judged. For example, assume that a porous sand having an $F$ factor of less than 15 was under consideration. If the mud filtrate resistivity were 0.5 meter-ohms, the resistivity of the invaded zone, if completely flushed, would be $15 \times 0.5 = 7.5$. Thus the observed resistivity values of this sand up to approximately 7.5 meter-ohms could be due to invasion.

ACKNOWLEDGMENT

Cooperation of the Shell Oil Co., Inc., and permission to publish this paper are gratefully acknowledged. The resistivity measurements on the numerous cores were performed under the supervision of S. H. Rockwood and J. H. McQuown, of the Shell Production Laboratories.

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## DISCUSSION

*(H. F. Beardmore presiding)*

S. W. WILCOX,* Tulsa, Okla.—This paper recalls some of my own observations on the correlation of the electrical resistance of earth materials with their other physical properties. While Geophysical Engineer for the Department of Highways, of the State of Minnesota, from 1933 until 1936, I was primarily engaged in conducting earth-resistivity surveys prospecting for and exploring sand and gravel deposits. This work was done by two field parties using equipment of the Gish-Rooney type, and was carried out in every part of the state, both winter and summer.

In brief, when a sand or gravel prospect was discovered, in any way, it was detailed by the resistivity survey to outline its extent and to locate test holes for field and laboratory sample analysis. This survey consisted of a grid of "steptraverses" of one or more electrode separations, and for each an "iso-ohm," or equal resistance contour plan map, was drawn.

Several thousand earth-resistivity readings were taken over more than one hundred prospects. In some instances the test pitting was started before the completion of electrical survey and their findings were soon available for checking any suspected correlation theory and confirming what subsurface factors were being measured and how effectively.

From accepted earth-resistivity theory, it follows that within a definite sphere surrounding the electrodes the apparent resistance measurement is uniquely determined from the specific resistance and position of each and all of the particles making up the sphere. Any rational interpretation of these apparent resistance measurements is possible only for the simplest combinations of particles and their specific resistances. Fortunately, soils, subsoils and subsurface rocks, with their embodied fluids and gases, vary greatly in this property among themselves. For example, clay appears to have an average specific resistance of approximately 50 to 150 foot-ohms, whereas for sand and gravel the specific resistance is roughly from 2000 to 5000 foot-ohms. The important feature is the great absolute differences in resistance, consequently a resistance profile across a buried lens of sand or gravel surrounded by clay produces a striking response.

In spite of the amount of control available and the freedom for selecting various electrode intervals, no reliable quantitative predictions could be made that were not related to boundary surfaces. The probable depth to the first discontinuity—namely, the clay-sand contact—could be determined fairly accurately if the thickness of the sand body was considerable. When the depth to the sand was known from independent data, or could be assumed to be constant, it was possible to predict its thickness. If both were known, a good guess might be made regarding the depth to the water table; and, in addition, if all these were known, a surmise could be made about the quality of the sand; i.e., whether it contained organic material or was weathered. Perhaps if the degrees of control were sufficient the porosity of the sand, its grain size, or even its temperature might be predicted.

I observed that few of these variables, even the ones that generally contribute to the bulk of the readings, could be quantitatively separated without additional independent data; therefore my interpretation was necessarily empirical and based on experience. Fortunately, in sand and gravel prospecting the economically most important factors contribute their effects in the same direction. A high apparent resistance indicates either a thin body of highly resistant gravel near the surface, or a thicker one overlain with more clay stripping. Clean gravel is more resistant than weathered, and hard gravel more so than soft.

* Seismograph Service Corporation.

In practical terms, I found that an apparent resistance reading of 500 foot-ohms for a 20-ft. electrode separation recorded over ground or glacial moraines of southern Minnesota reliably suggested a deposit of sand or gravel worth further investigation. As a matter of record, prospecting in the part of the state where these materials are very scarce, less than 3 per cent of the test holes located on the geophysical information failed to yield granular materials of commercial quality and quantity for at least highway subgrade treatment. Varying the electrode interval gave additional confirmation as to the thickness of the deposit and very little else.

In connection with our field work, we made extensive laboratory studies, attempting to work out the relation between the moisture content of sand and gravel and its specific resistance. These apparently simple experiments were not of much help in clearing up my field interpretations. Several variables were very hard to control in the laboratory.

The analogy between this type of earth-resistivity mapping and electrologging is close. The first measures electrical impedance along a surface generally parallel to the bedding planes; the latter, up a borehole more or less perpendicular to them. The same general limitations and possibilities appear to be common to both methods. Obviously, controls for checking are easier to obtain for plan mapping than for well logging within the depth of effective penetration.

My interpretation problems appeared to be essentially similar to those of electrical well logging where the operator, after observing the character of the resistance and the self-potential curves, tells his client whether pipe should be set. The accuracy of his prediction is based largely on experience and not on slide-rule calculations.

Mr. Archie's paper suggests an experimental attack for expanding and improving the interpretation technique of electrical well logging. Any contribution of this nature that increases its effectiveness is of great value to the petroleum industry. I offer my own experiences and observations to emphasize that he has tackled a difficult research problem and wish him luck.

Dr. A. G. Loomis,* Emeryville, Calif.—In the laboratory, we take into account the variations in measured resistivities of sands and tap water by finding out the cause of the variations in resistivity. That is, if the tap water itself varied from day to day, its electrolyte content must vary from day to day and chemical analysis would indicate the change. If sands did not give consistent resistivity readings, the character of the sands (in other words, the formation resistivity factor) probably changed or the kind and amount of water contained in the sand must have varied.

* Shell Development Co.

**BAKER, E.T., 1979**

**STRATIGRAPHIC AND HYDRGEOLOGIC FRAMEWORK**

**OF PART OF THE COASTAL PLAIN OF TEXAS**

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# STRATIGRAPHIC AND HYDROGEOLOGIC FRAMEWORK OF PART OF THE COASTAL PLAIN OF TEXAS

By

E. T. Baker, Jr.

Open-File Report 77-712

Prepared in cooperation with
the Texas Water Development Board

March 1978

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# STRATIGRAPHIC AND HYDROGEOLOGIC FRAMEWORK OF PART OF THE COASTAL PLAIN OF TEXAS

By

E. T. Baker, Jr.

## ABSTRACT

The subsurface delineation of hydrogeologic units of Miocene and younger age and stratigraphic units of Paleocene to Holocene age establishes an interrelationship of these units Statewide across much of the Coastal Plain of Texas. The 11 dip sections and 1 strike section, which extend from the land surface to 7,600 feet (2,316 meters) below sea level, provide continuity of correlation from the outcrop to the relatively deep subsurface. Sand containing water with less than 3,000 milligrams per liter of dissolved solids, which is shown on the sections, serves as an index of water availability of this quality.

## INTRODUCTION

This report has been prepared to illustrate the stratigraphic and hydrogeologic framework of a part of the Coastal Plain of Texas from the Sabine River to the Rio Grande. It is the outgrowth of a project that has as its ultimate objective the construction of a digital ground-water flow model, if feasible or desirable, of at least a part of the Miocene aquifers in the Gulf Coastal Plain of Texas. The model would serve as a tool for planning the development of the ground-water supplies. Work on the project is being done by the U.S. Geological Survey in cooperation with the Texas Water Development Board.

During the course of delineating the Miocene aquifers, which is basic to the design and development of the model, the scope of the study was broadened to include delineations of other hydrogeologic units, as well as delineations of stratigraphic units. As a result, units ranging in age from Paleocene to Holocene were delineated (table 1). A relationship of stratigraphic units to designated hydrogeologic units was thus established Statewide.

Eleven dip sections and one strike section are included in this report. The dip sections are spaced about 50 miles (80 km) apart with the most easterly one being near the Sabine River and the most southerly one being near the Rio Grande. Each dip section is about 100 miles (161 km) long and extends from near the coastline to short distances inland from the outcrop of the oldest Miocene formation--the Catahoula Tuff or Sandstone. The strike section, which is about 500 miles (804 km) long (in three segments), extends from the Sabine River to the Rio Grande and joins the dip sections at common control points. This section is from 50-75 miles (80-121 km) inland from the Gulf of Mexico and is essentially parallel to the coastline. The location of the sections and the Catahoula outcrop are shown on figure 1.

The sections extend from outcrops at the land surface to maximum depths of 7,600 feet (2,316 m) below sea level. Selected faunal occurrences, where known or inferred by correlation from nearby well logs, are included. The extent of sand that contains water having less than 3,000 mg/L (milligrams per liter) of dissolved solids was estimated from the electrical characteristics shown by the logs. This information is included on all of the sections.

Although faulting is common in the Coastal Plain and is complex in some areas, all faults have been omitted from the sections to maintain continuity of the stratigraphic and hydrogeologic boundaries. The disadvantage of such omission is, of course, the representation of an unrealistic and simplistic picture of unbroken stata with uninterrupted boundaries. In reality, many of the faults have not only broken the hydraulic continuity of the strata but more importantly have become barriers to fluid flow or conduits for cross-formational flow. The sections are presented in this report as figures 2-15.

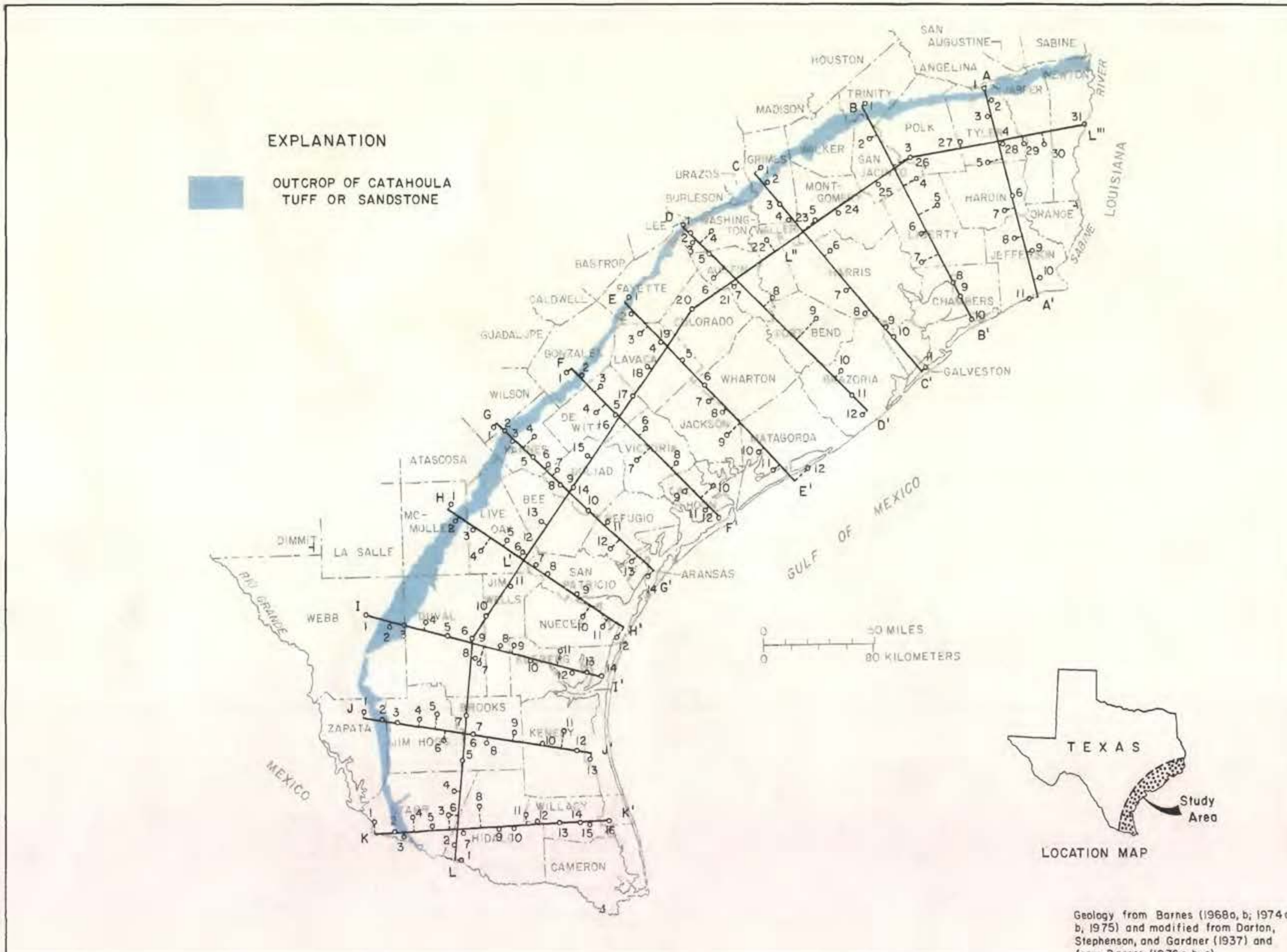


FIGURE 1.-Index map showing location of sections

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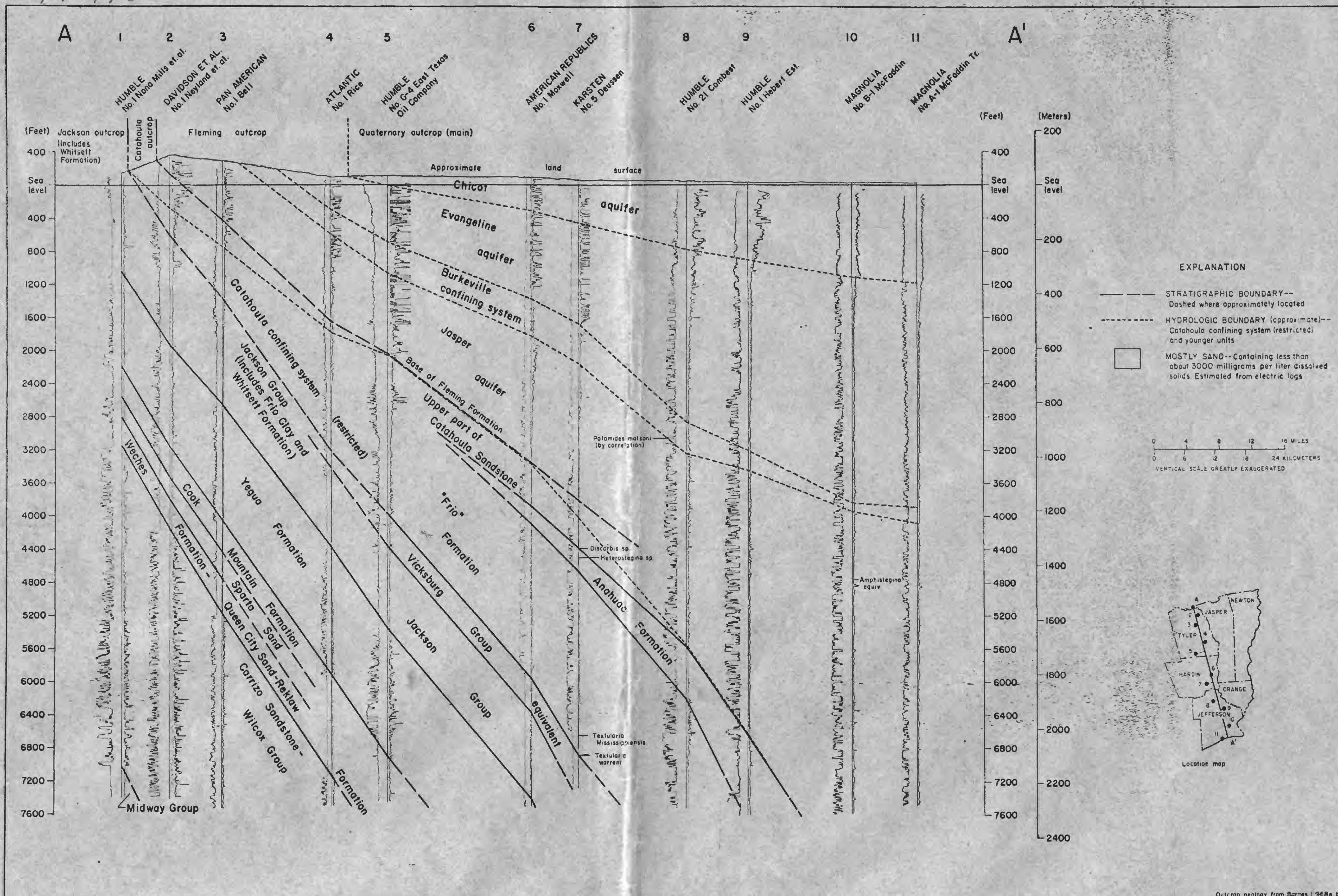


FIGURE 2.-Stratigraphic and hydrogeologic section A-A'

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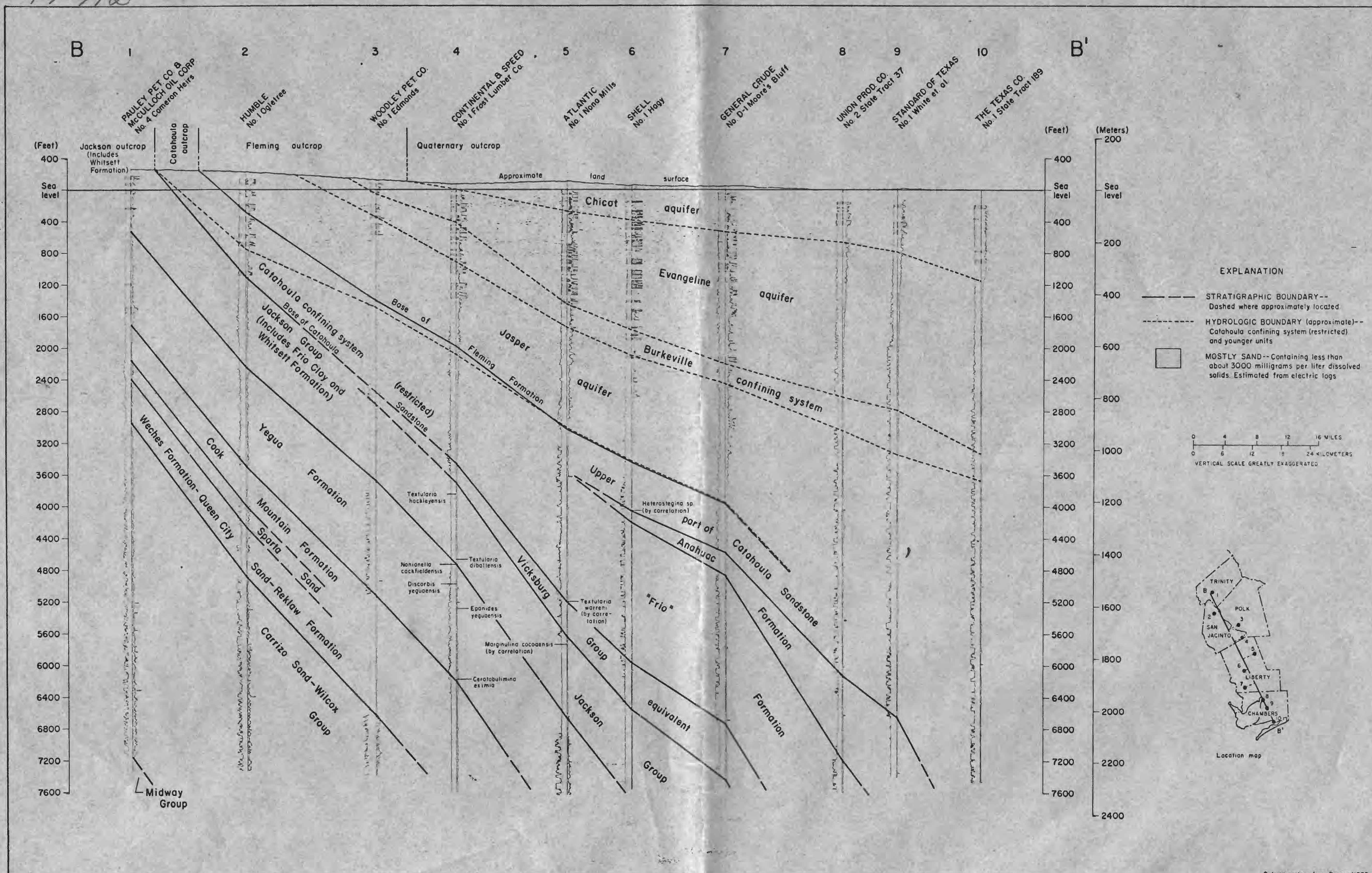


FIGURE 3.-Stratigraphic and hydrogeologic section B-B'

5

77-712

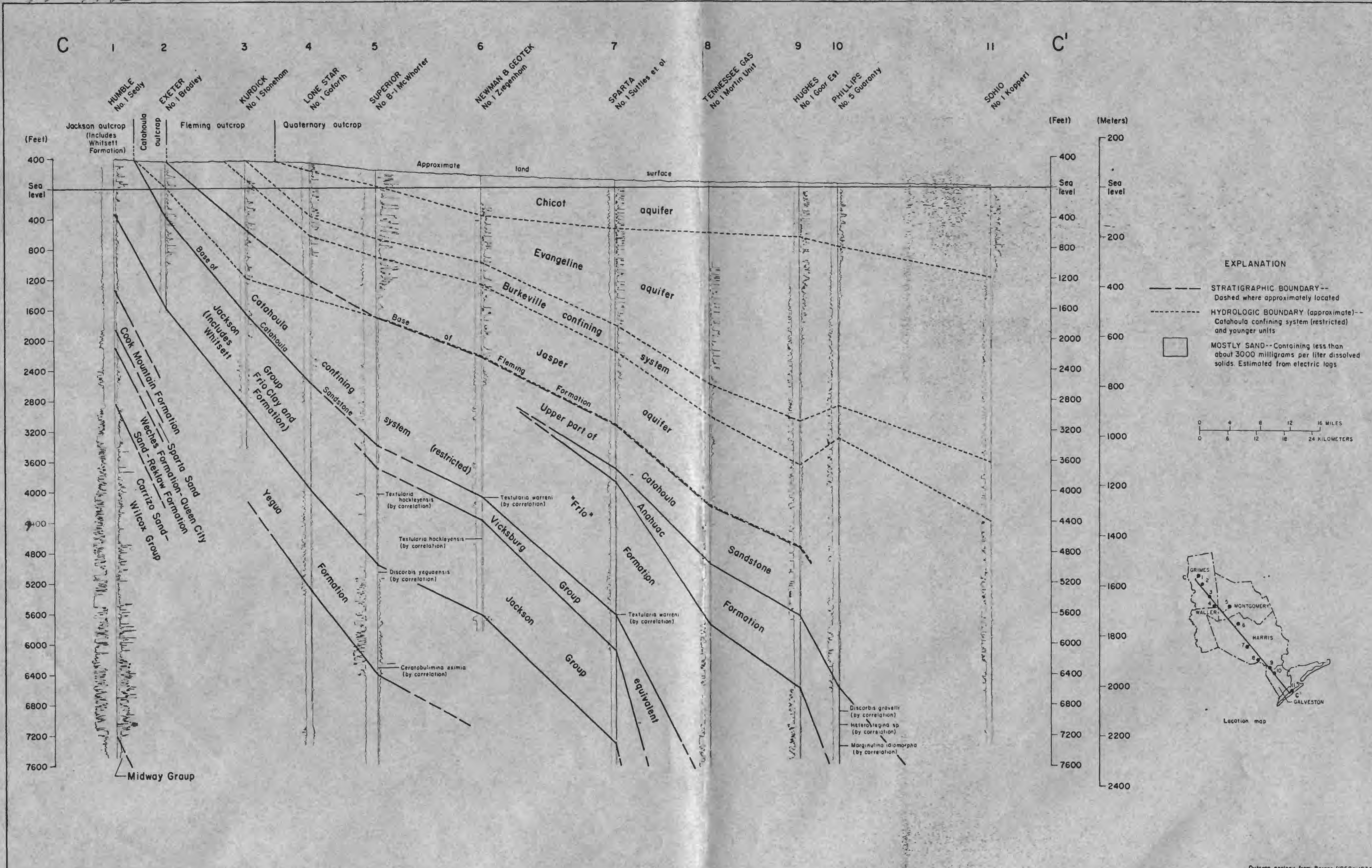

FIGURE 4.-Stratigraphic and hydrogeologic section C-C'

6

77-712

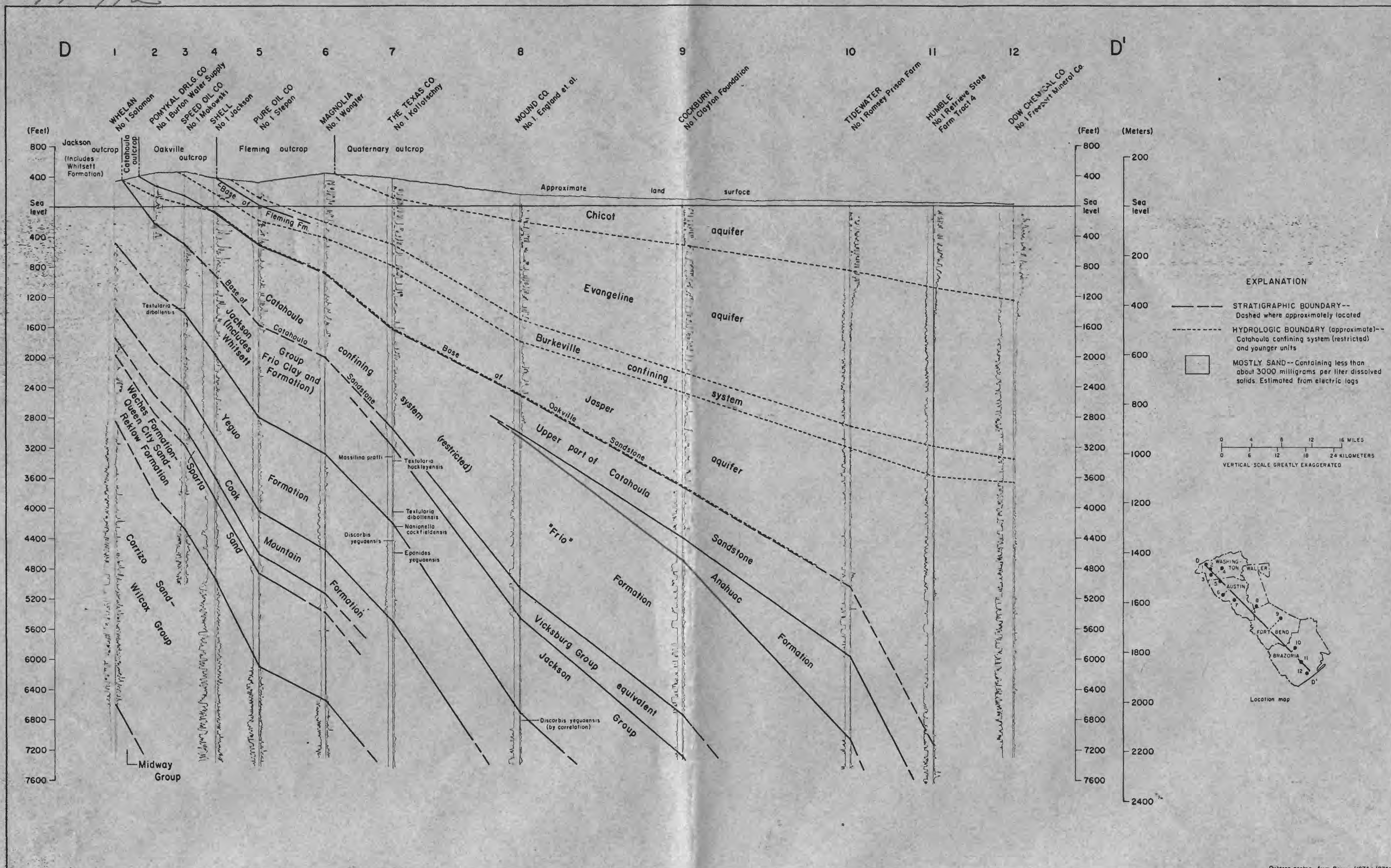


FIGURE 5.-Stratigraphic and hydrogeologic section D-D'

77-712

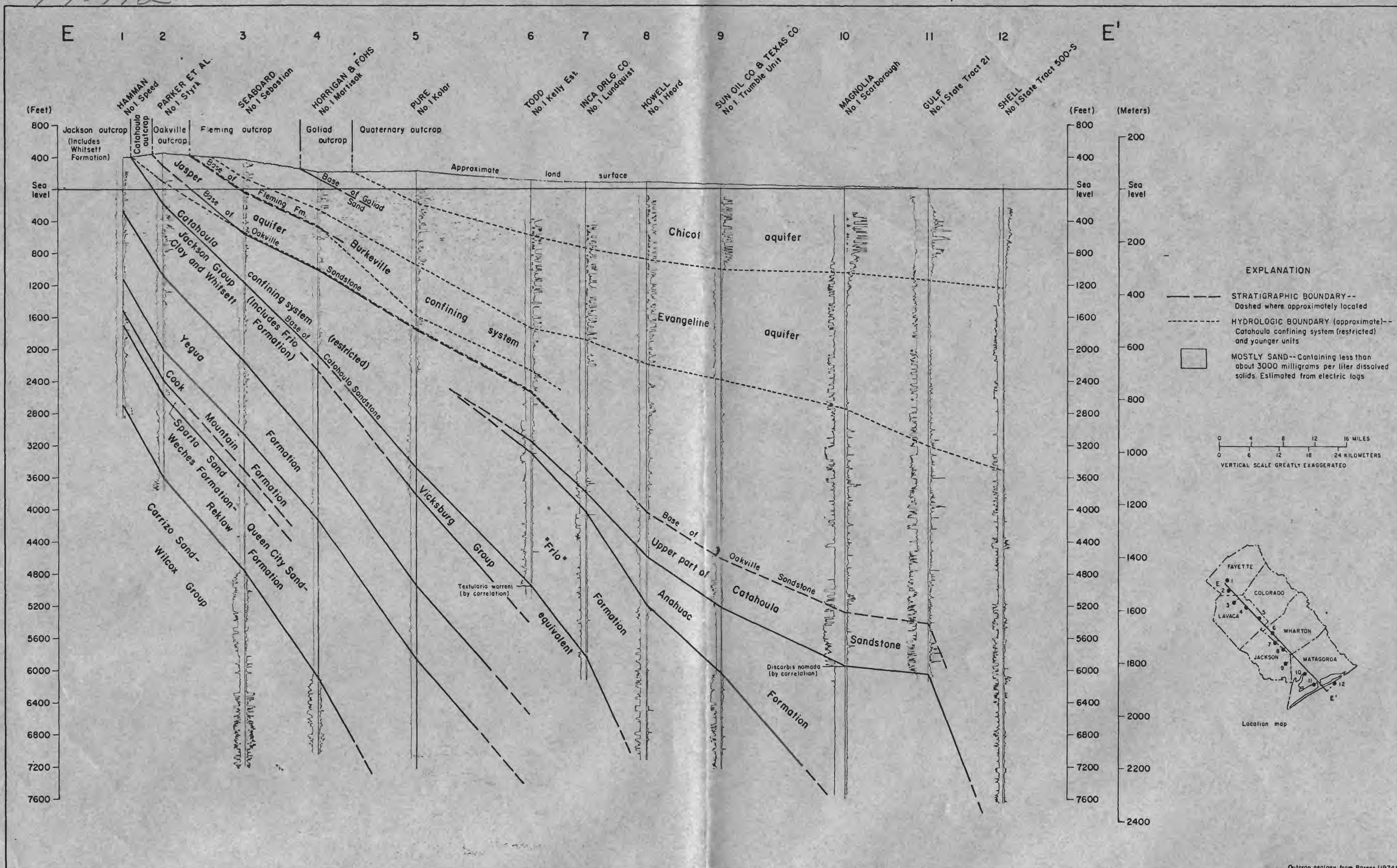


FIGURE 6.-Stratigraphic and hydrogeologic section E-E'

77-712

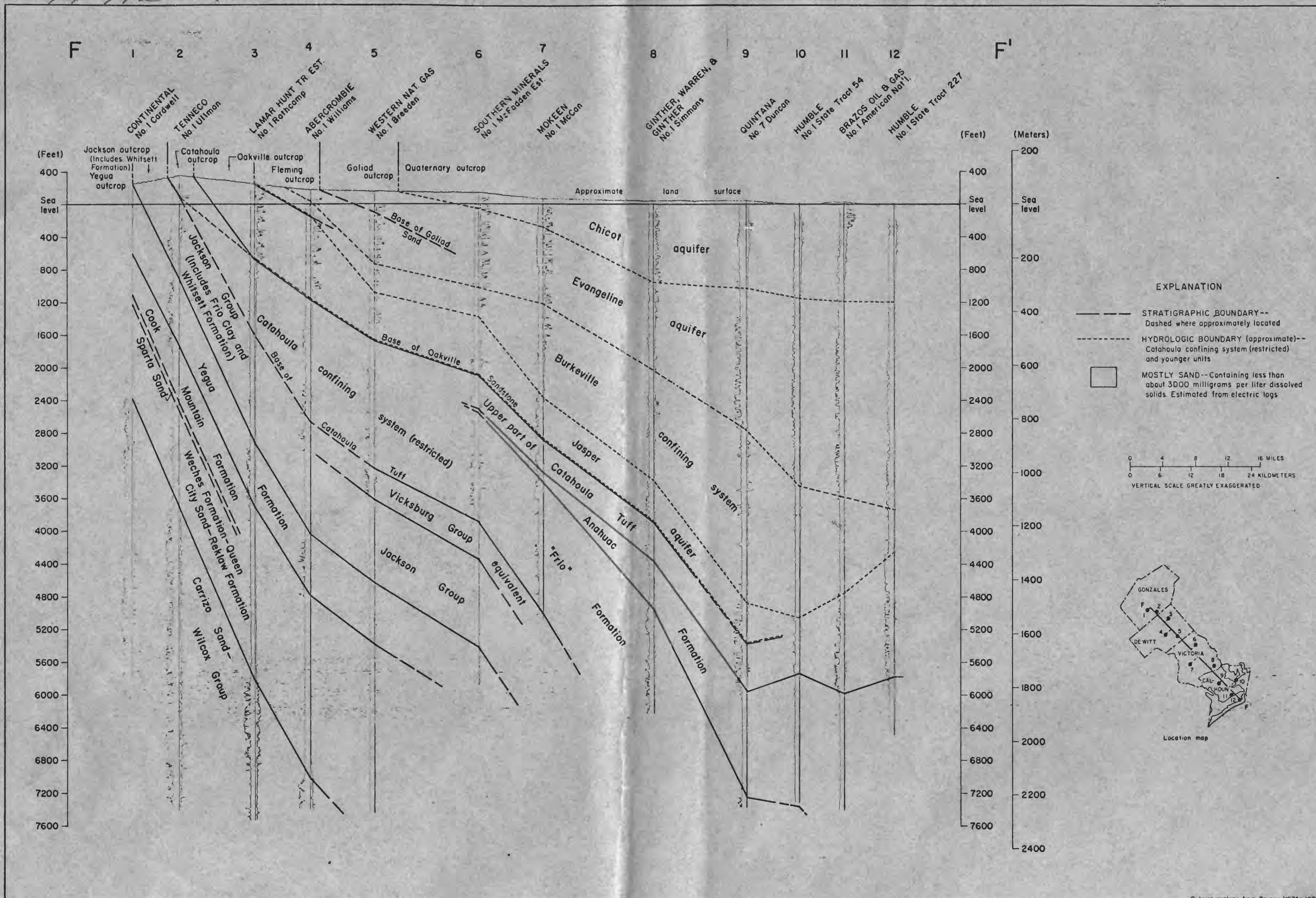


FIGURE 7.-Stratigraphic and hydrogeologic section F-F'

77-712

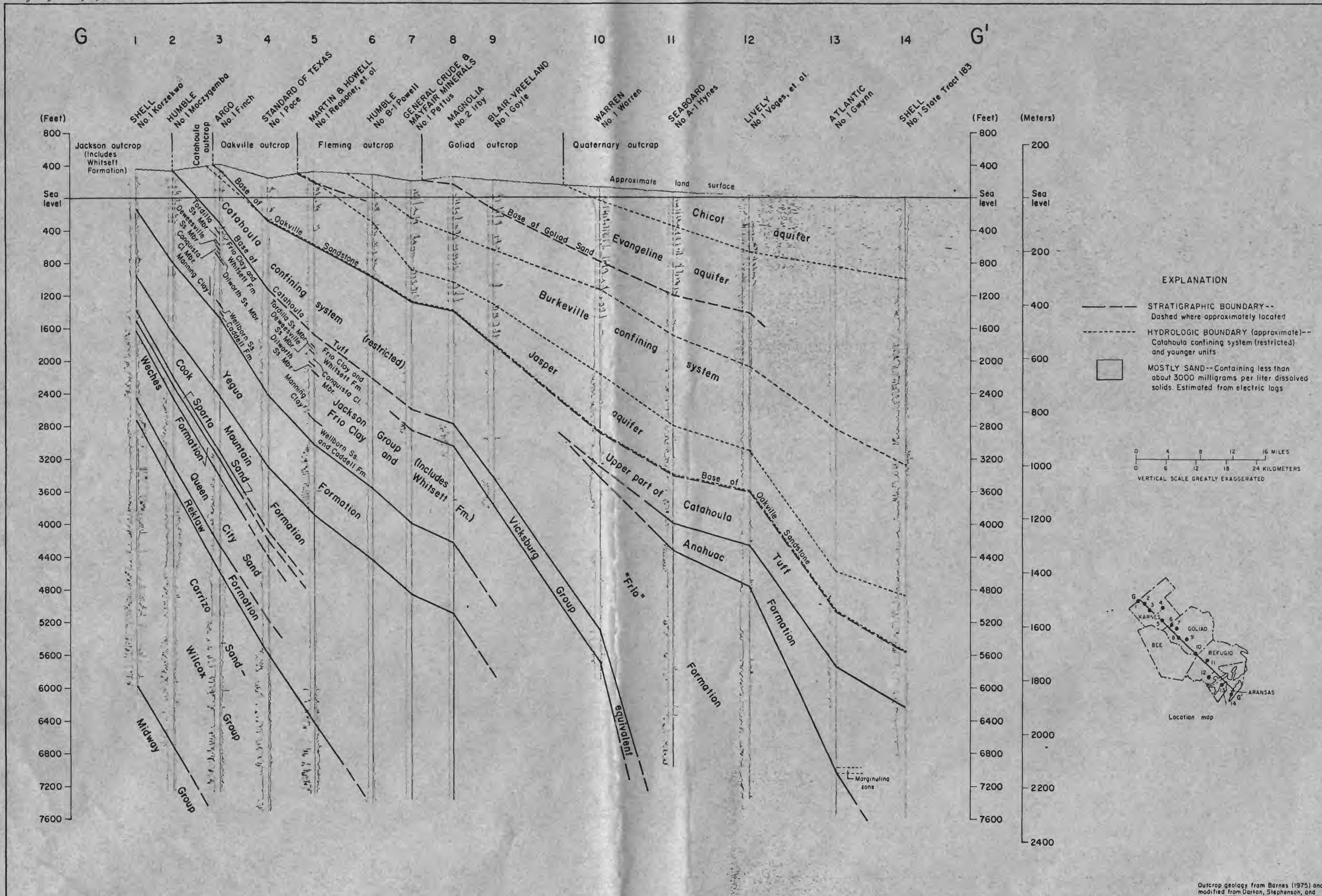


FIGURE 8.-Stratigraphic and hydrogeologic section G-G'

77-712

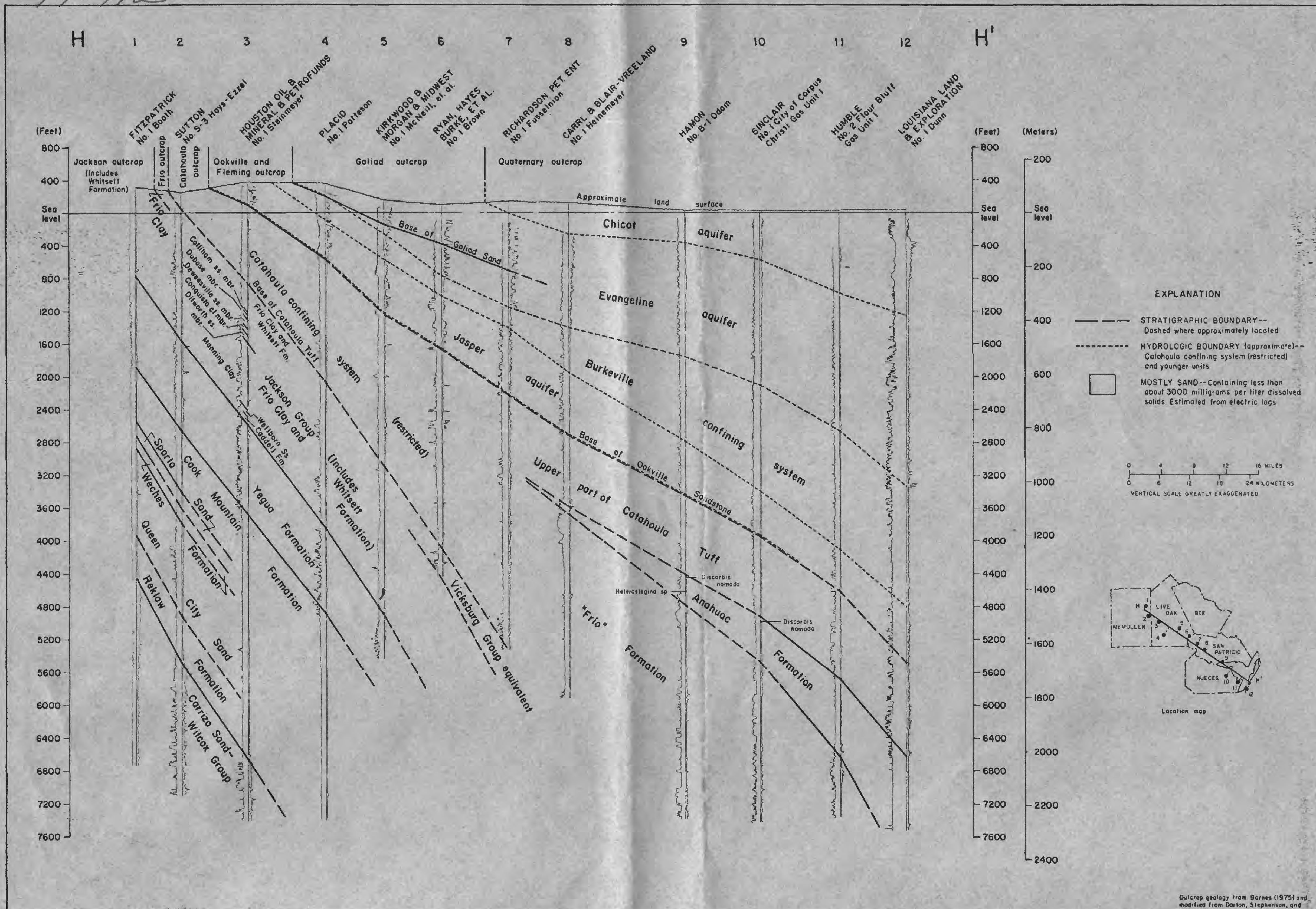


FIGURE 9.-Stratigraphic and hydrogeologic section H-H'

11

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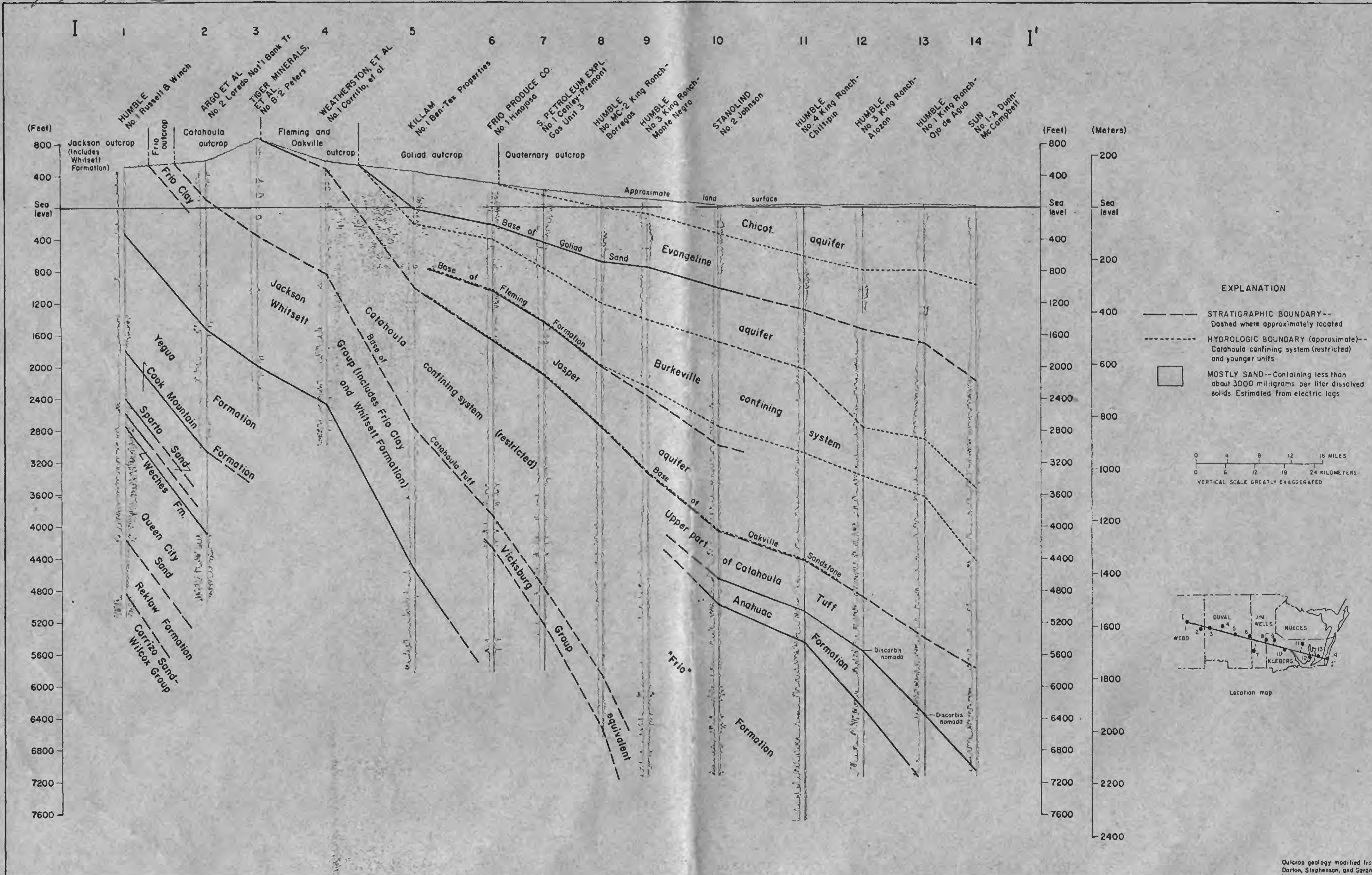


FIGURE 10.-Stratigraphic and hydrogeologic section I-I'

77-712

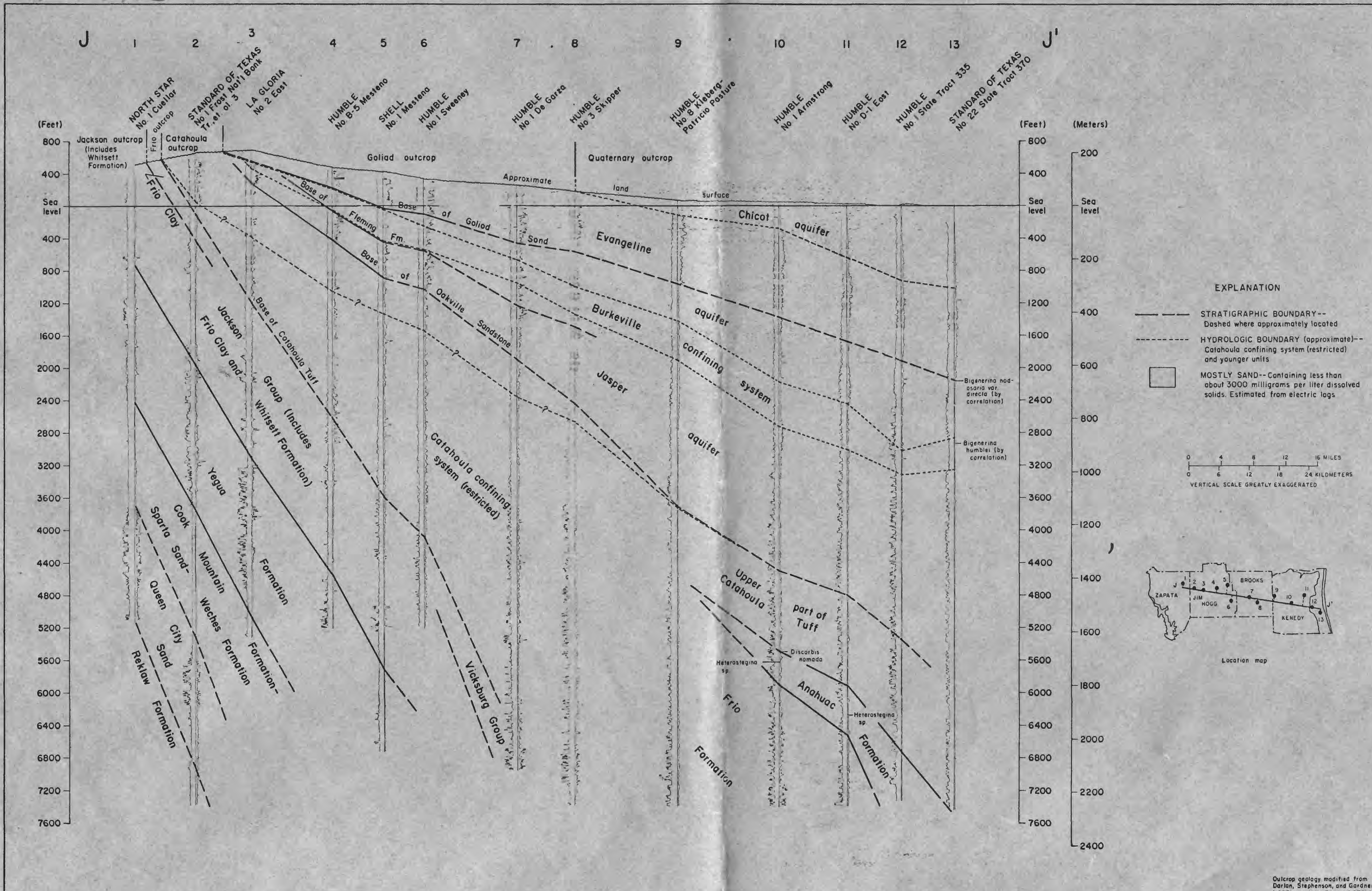


FIGURE 11.-Stratigraphic and hydrogeologic section J-J'

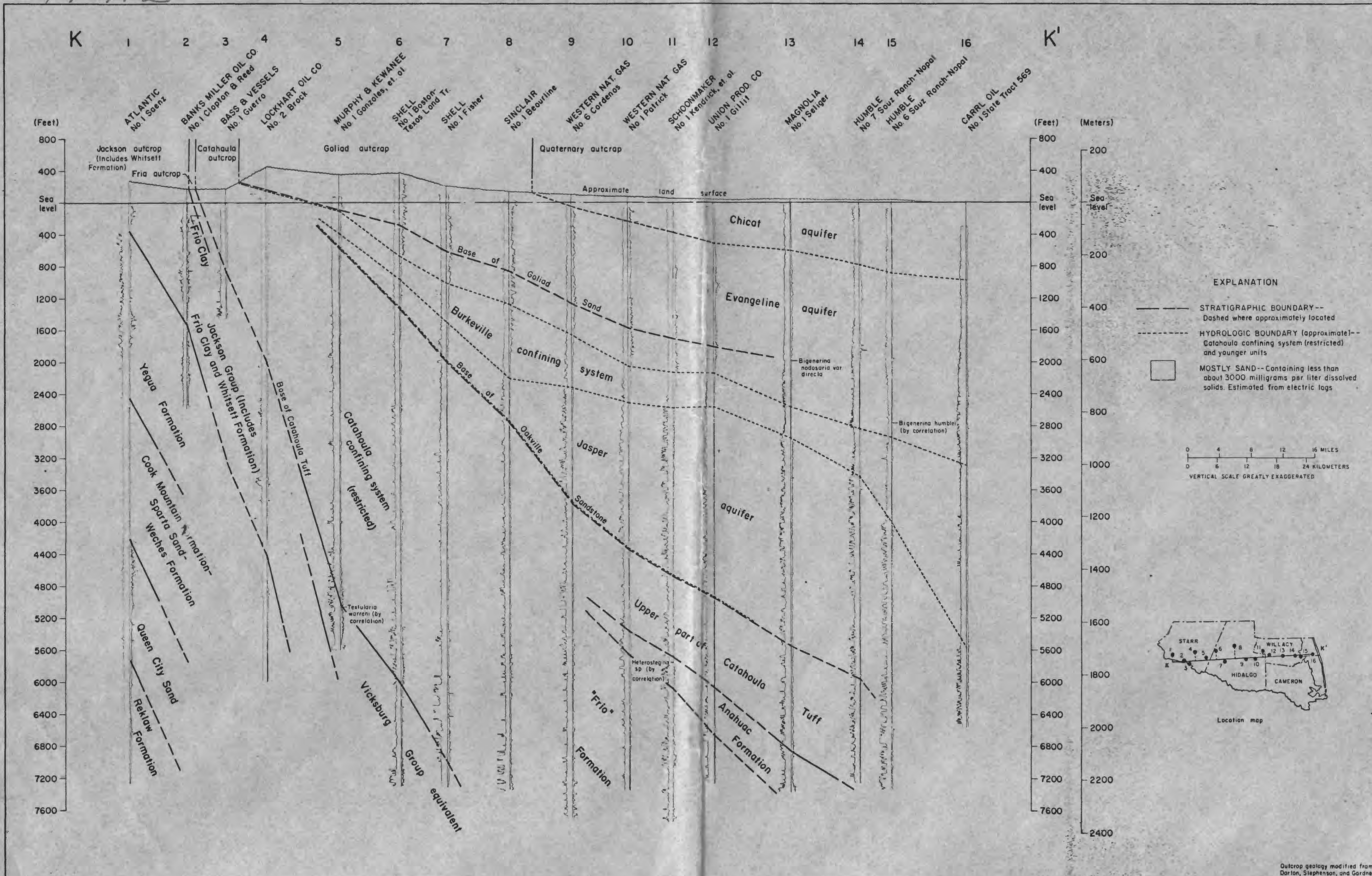


FIGURE 12.-Stratigraphic and hydrogeologic section K-K'

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77-712

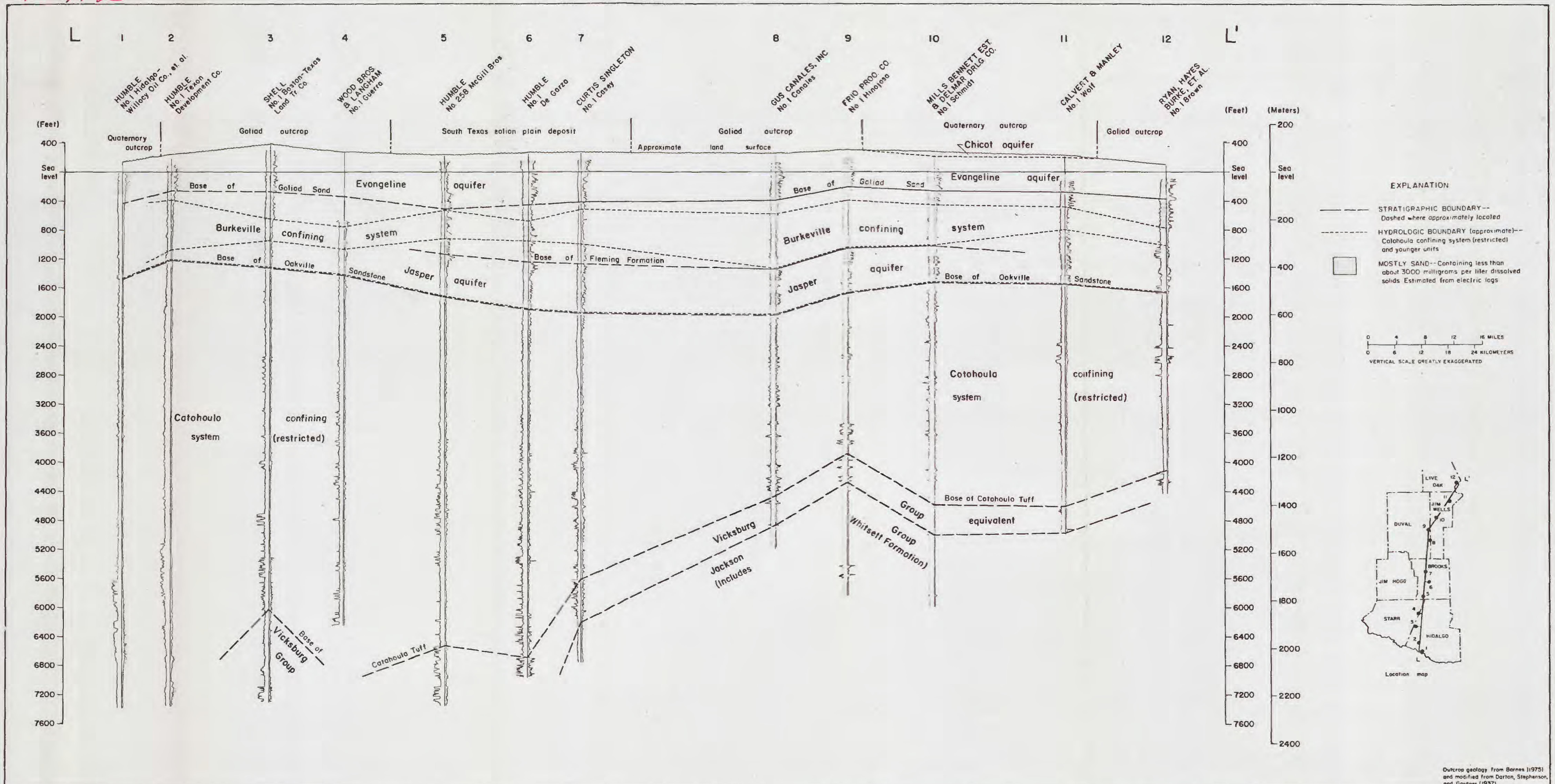


FIGURE 13.-Stratigraphic and hydrogeologic section L-L'

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FIGURE 14.-Stratigraphic and hydrogeologic section L'-L"

16

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77-712

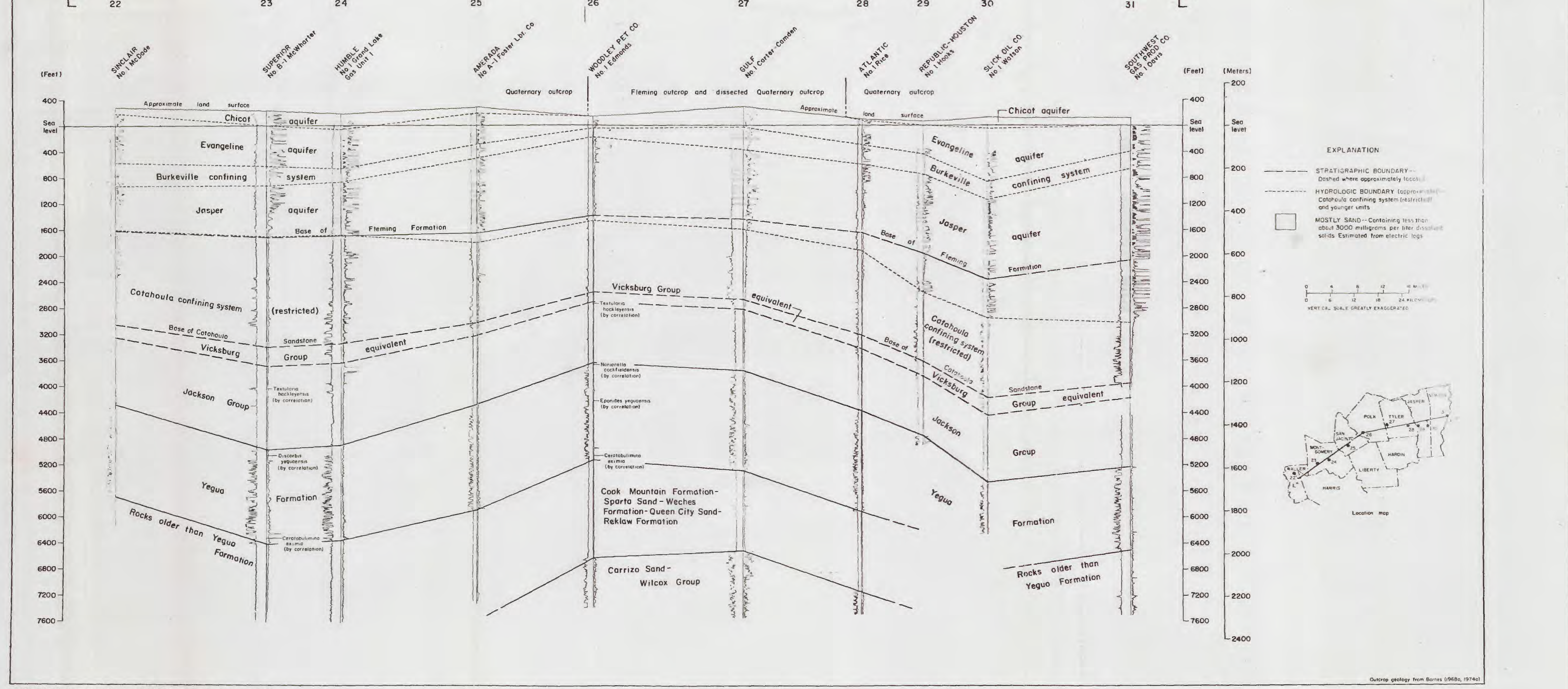


FIGURE 15. Stratigraphic and hydrogeologic section L''-L'''

Table 1.--Stratigraphic and Hydrogeologic Framework of Part of the Coastal Plain of Texas

| Era | System | Series | Stratigraphic Units | Hydrogeologic Units | Selected Faunal Markers | Remarks |
|---|---|---|---|---|---|---|
| CENOZOIC | Quaternary | Holocene | Alluvium | Chicot aquifer | | Quaternary System undifferentiated on sections. |
| | | Pleistocene | Beaumont Clay | | | |
| | | | Montgomery Formation | | | |
| | | | Bentley Formation | | | |
| | | | Willis Sand | | | |
| | Tertiary | Pliocene | Goliad Sand | Evangeline aquifer | | Goliad Sand overlapped east of Lavaca County. |
| | | Miocene | Fleming Formation | Burkeville confining system | Potamides matsoni<br>Bigenerina nodosaria var. directa<br>Bigenerina humblei<br>Amphistegina sp. | |
| | | | Oakville Sandstone | Jasper aquifer | | Oakville Sandstone included in Fleming Formation east of Washington County. |
| | | Miocene / ? Oligocene(?) ? | Surface: Catahoula Tuff or Sandstone; Subsurface: Upper part of Catahoula Tuff or Sandstone | Jasper aquifer | | Catahoula Tuff designated as Catahoula Sandstone east of Lavaca County. |
| | | | Subsurface: Anahuac Formation | Catahoula confining system (restricted) | Discorbis nomada<br>Discorbis gravelli<br>Heterostegina sp.<br>Marginulina idiomorpha | Anahuac and "Frio" Formations may be Oligocene in age. |
| | | | Subsurface: "Frio" Formation | | Textularia mississippiensis | |
| | | Oligocene(?) | Surface: Frio Clay; Subsurface: Vicksburg Group equivalent | Not discussed as hydrologic units in this report. | Textularia warreni | Frio Clay overlapped or not recognized on surface east of Live Oak County. |
| | | ? Oligocene(?) / Eocene ? | Jackson Group — Whitsett Formation — Fashing Clay Member | | | Indicated members of Whitsett Formation apply to south-central Texas. Whitsett Formation east of Karnes County may be, in part or in whole, Oligocene in age. |
| | | | Jackson Group — Whitsett Formation — Calliham Sandstone Member or Tordilla Sandstone Member | | | |
| | | Eocene | Jackson Group — Whitsett Formation — Dubose Member | | Marginulina cocoaensis | |
| | | | Jackson Group — Whitsett Formation — Deweesville Sandstone Member | | | |
| | | | Jackson Group — Whitsett Formation — Conquista Clay Member | | Textularia hockleyensis | |
| | | | Jackson Group — Whitsett Formation — Dilworth Sandstone Member | | Massilina pratti | |
| | | | Jackson Group — Manning Clay | | | |
| | | | Jackson Group — Wellborn Sandstone | | Textularia dibollensis | |
| | | | Jackson Group — Caddell Formation | | | |
| | | | Claiborne Group — Yegua Formation | | Nonionella cockfieldensis | |
| | | | Claiborne Group — Cook Mountain Formation | | Discorbis yeguaensis | |
| | | | Claiborne Group — Sparta Sand | | Eponides yeguaensis | |
| | | | Claiborne Group — Weches Formation | | Ceratobulimina eximia | |
| | | | Claiborne Group — Queen City Sand | | | |
| | | | Claiborne Group — Reklaw Formation | | | |
| | | | Claiborne Group — Carrizo Sand | | | |
| | | | Wilcox Group | | | |
| | | Paleocene | Midway Group | | | |

## Acknowledgments

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## Metric Conversions

For those readers interested in using the metric system, the metric equivalents of English units of measurements are given in parentheses. The English units used in this report have been converted to metric units by the following factors:

| From | | Multiply | To obtain | |
|---|---|---|---|---|
| Unit | Abbreviation | by | Unit | Abbreviation |
| feet | -- | 0.3048 | meters | m |
| miles | -- | 1.609 | kilometers | km |

# STRATIGRAPHIC FRAMEWORK

## General Features of Deposition and Correlation Problems

Cenozoic sediments that underlie the Coastal Plain of Texas are tens of thousands of feet thick at the coastline. These clastic sediments of sand, silt, and clay represent depositional environments ranging from nonmarine at the outcrops of most units to marine where the units may carry a distinctive suite of fossils. Oscillations of ancient seas and changes in amount and source of sediments that were deposited caused facies changes downdip and along strike. For example, a time-stratigraphic unit having age equivalency may consist of sand in one area, sandy clay in a second area, and clay in a third area. Subsidence of the basin of deposition and rising of the land surface caused the stratigraphic units to thicken Gulfward. Growth faults (faults that were more or less continuously active) greatly increased the thickness of some stratigraphic units in short distances. All of these factors contributed to the heterogeneity of the units from place to place, which in turn makes correlation difficult.

## Stratigraphic Units

In the discussion to follow, emphasis will be placed on stratigraphic units that are designated in this report as Miocene in age. Many of the correlation problems of the Cenozoic deposits involve these units to a large degree. Also the main thrust of this report is directed at the Miocene in keeping with the ultimate objective of modeling the flow in the Miocene aquifers.

The stratigraphic nomenclature used in this report was determined from several sources and may not necessarily follow the usage of the U.S. Geological Survey.

### Pre-Miocene

Delineation of most of the pre-Miocene units of Cenozoic age present relatively few problems of significance. This is especially true of the pre-Jackson units (Midway Group to Yegua Formation). The top of the Carrizo Sand of the Claiborne Group (included with the underlying Wilcox Group on the sections) can be easily delineated, which makes the position of the unit ummistakable in the subsurface. From about the Sabine River to the San Marcos Arch (section F-F', fig. 7, is centered over this structural feature) the top of the Carrizo-Wilcox is about 3,000 feet (914 m) beneath the landward edge of the Catahoula outcrop. Southward from the San Marcos Arch into the Rio Grande Embayment of south Texas, its position steadily increases in depth to more than 7,000 feet (2,134 m) at the western end of section K-K' (fig. 12).

Facies changes occur downdip in the Sparta and Queen City Sands of the Claiborne Group, and where these units grade into clay, delineation on a time-stratigraphic basis is virtually impossible from electrical-log interpretation. The same problem affects the Yegua Formation of the Claiborne Group, although the Yegua remains sandy for greater distances downdip. It can be delineated by lithology on most of the sections in this report. Also, the presence of important faunal markers such as *Nonionella cockfieldensis* and *Ceratobulimina eximia* aid in locating the approximate top and base, respectively, of the Yegua, regardless of its lithology.

The delineation of the Jackson Group is significant in establishing the framework for the Miocene units. This is because the outcropping Frio Clay of Oligocene(?) age of south Texas is completely overlapped in Live Oak County by the Miocene Catahoula (or is not recognized on the surface east of this area). The overlap places the Catahoula in contact with part of the Whitsett Formation, the uppermost formation of the Jackson Group in this area. East of the overlap to the Sabine River, careful attention was required to properly separate on the sections the tuffaceous sand and clay interbeds of the Whitsett from the tuffaceous sand and clay interbeds of the overlying Catahoula. From Live Oak County southward, the outcropping Frio Clay separates the Whitsett Formation from the Catahoula Tuff.

The age of the Whitsett, although shown in table 1 as Eocene in south-central Texas, may be at least in part Oligocene in the eastern part of the State. Eargle, Dickinson, and Davis (1975) consider the Whitsett to be Eocene at least from central Karnes County to southern McMullen County. Barnes (1975) likewise considers the Whitsett to be unquestionably Eocene no farther east than central Karnes County. From this area to the Sabine River, Dr. V. E. Barnes (written commun., Apr. 5, 1971) states that the Whitsett may "climb timewise eastward" and be largely Oligocene in east Texas; that the Nash Creek Formation of Louisiana, which is considered to be largely Oligocene, is equivalent to the Whitsett as mapped in Texas near the Sabine River; and the Oligocene vertebrates, which Dr. J. A. Wilson (Dept. of Geologic Sciences, University of Texas at Austin) collected from the Whitsett in Washington County, show that this formation is at least part Oligocene at that site. Because of the probability that the Whitsett is Oligocene, in part or in whole in much of the area, the delineation of the Eocene Jackson Group is shown on the sections to include the Whitsett Formation.

The Frio Clay of Oligocene(?) age has been a controversial unit for decades. Geologists still do not agree on its subsurface equivalents or if it is even a separate stratigraphic unit from the Catahoula. The fact that many geologists have mapped the unit from Live Oak County to the Rio Grande lends support to the existence of the Frio Clay as a formation. The Geologic Atlas of Texas (Barnes, 1976a,b,c) shows that the Frio is mapped separately as a distinct formation from its overlap in Live Oak County to southern Webb County; from there to the Rio Grande, the Frio is undifferentiated from the Catahoula. The Frio outcrop that was used for control at the surface on the dip sections H-H' to K-K' (figs. 9-12) was modified from Darton, Stephenson, and Gardner (1937) and from Barnes (1976a,b,c). East of the overlap in Live Oak County the Frio is presumed to be present in the shallow subsurface beneath the Catahoula with the erosional edge probably only a few miles downdip from the edge of the Catahoula outcrop.

The Frio Clay at the surface has been interpreted by the author to be, at least in part, the nonmarine time-equivalent of the subsurface Vicksburg Group--a marine biostratigraphic unit of Oligocene age that crops out east of the Sabine River and is characterized by the foraminifer Textularia warreni. The relationship is supported by Deussen and Owen (1939, p. 1630) and by the Houston Geological Society (1954). The Vicksburg equivalent east of Karnes County may also be at least a partial time-equivalent of the Whitsett, whose probable Oligocene age in this area may, in itself, indicate an equivalency. Ellisor (1944, fig. 1, and p. 1365) supports this probability and illustrates the relationship in a geologic section. Additionally, this probability is supported by the apparent correlation of the outcrop of the Vicksburg Group in Louisiana near the Sabine River as shown on the geologic map of Louisiana (Wallace, 1946) with the outcrop of the Whitsett Formation as shown on the Geologic Atlas of Texas (Barnes, 1968b). This relationship may be inferred on the dip sections from A-A' to at least F-F' (figs. 2-7) where the Vicksburg equivalent, if projected to the outcrop, would intersect the outcropping Whitsett.

## Miocene

The stratigraphic framework of the units that are designated in this report as Miocene in age is complex and controversial, perhaps more so than any other Cenozoic units. Geologists do not agree which units on the surface or in the subsurface are Miocene nor do they agree as to the relationship of the surface and subsurface units. The correct relationship may never be determined because faunal markers, which exist in places in the subsurface, do not extend to the outcrop; and the heterogeneity of the sediments does not facilitate electrical-log correlations.

The outcropping stratigraphic units that are assigned to the Miocene in this report are, from oldest to youngest, the Catahoula Tuff or Sandstone, Oakville Sandstone, and Fleming Formation. The "Frio" Formation, Anahuac Formation, and a unit that is referred to in this report as the upper part of the Catahoula Tuff or Sandstone are assigned by the author as possible downdip equivalents of the surface Catahoula although the Anahuac and "Frio" Formations may be Oligocene in age. Table 1 and the dip sections (figs. 2-12) illustrate this relationship.

The outcrop of the Catahoula, a pyroclastic and tuffaceous unit, has been mapped independently by various geologists with little modification from the Sabine River to the Rio Grande. Darton, Stephenson, and Gardner (1937) modified the unit's name from Catahoula Tuff to Catahoula Sandstone east of Lavaca County where the formation becomes more sandy.

It may be seen on the sections that the thickness of the surface Catahoula increases downdip at a large rate in the subsurface to eventually include, when the Anahuac Formation is reached, the "Frio" Formation which underlies the Anahuac, the Anahuac, and the upper Catahoula unit. Deussen and Owen (1939, figs. 5, 6, p. 1632, and table 1), in a study of the surface and subsurface formations in two typical sections of the Texas Coastal Plain (one in east Texas, the other in south Texas) agree with this relationship. They disagree, however, with these units being Miocene and assign them to the Oligocene. Some oil-company geologists consider the Anahuac and "Frio" as separate formations (unrelated to the Catahoula) in the subsurface and also assign them to the Oligocene. As a consequence of this usage, the upper Catahoula unit of this report is then usually referred to as "Miocene," which term is used instead of, or interchangeably with, Fleming. Holcomb (1964, fig. 2) in a study of the subsurface "Frio" Formation of south Texas places the "Frio" and Anahuac Formations, as well as the surface Catahoula in the Miocene, but does not admit to any Catahoula occurring above the Anahuac. He indicates that the "Fleming Formation" (Oakville Sandstone and Fleming Formation of this report) rests on the Anahuac. Dip sections, especially F-F', G-G', and H-H' (figs. 7-9), show unmistakably that the Catahoula-Oakville contact on the surface can be accurately traced far enough downdip by means of electrical logs to show that the clearly discernible contact is several hundred feet above the Anahuac. For this reason, the upper Catahoula unit above the Anahuac cannot be the Oakville. This contention is supported by Meyer (1939, p. 173) and by Lang and others (1950, plate 1).

The Anahuac Formation, despite the controversial attention it receives, is one of the most discernible formations in the subsurface. This marine biostratigraphic unit carries a rich microfauna of many tens of diagnostic species. These species are categorized into the _Discorbis_ zone, _Heterostegina_ zone, and _Marginulina_ zone, from youngest to oldest. Only a few of the diagnostic species (table 1) are included with the dip sections in this report. The updip limit of the marine facies of the Anahuac ranges in depth from about 2,500 feet (762 m) below land surface in east Texas to about 4,000 feet (1,219 m) in the Rio Grande Embayment in south Texas. The unit is quite sandy south of San Patricio County (south of section H-H', fig. 9) to the Rio Grande in contrast to its shaly character eastward from San Patricio County to the Sabine River.

The Oakville Sandstone and Fleming Formation are composed almost entirely of terrigenous clastic sediments that form sand and clay interbeds. Both formations are basically rock-stratigraphic units that are distinguished and delineated on the basis of lithologic characteristics. Their boundaries in the Coastal Plain of Texas are discernible contacts in some areas and arbitrary ones within zones of lithologic gradation in other areas.

The Oakville Sandstone is most prominent on the surface and in the subsurface in the central part of the Coastal Plain. Here its predominantly sandy character is distinguished from the underlying tuffaceous Catahoula and overlying Fleming, which is composed of clay and slightly subordinate amounts of sand.

The Oakville on the surface has been mapped as a formation from about the Brazos River at the Washington-Grimes County line to central Duval County, where its outcrop is overlapped by the Goliad Sand and remains overlapped to the Rio Grande. Beneath this overlap, the Oakville apparently decreases in thickness or loses its predominance of sand or both. In either case, its position in the shallow subsurface in parts of the Rio Grande Embayment is questionable on dip sections I-I' and K-K' (figs. 10, 12). In the vicinity of the Brazos River, the Oakville grades eastward into the base of the Fleming Formation and loses its identity. The position of the base of the Oakville in the deeper parts of the subsurface has been delineated on some of the sections merely as an approximation.

The Fleming Formation, the uppermost unit of Miocene age in the Coastal Plain, has been mapped on the surface in Texas from the Sabine River to central Duval County. From here, like the Oakville, it is overlapped by the Goliad Sand and remains beneath the Goliad to the Rio Grande.

The Fleming is lithologically similar to the Oakville but can be easily separated from the Oakville in some places by its greater proportion of clay. Plummer (1932, p. 744, 747) described the Lagarto as consisting of 75 percent marl or clay, 15 percent sand, and 10 percent silt, with the clay beds being thicker and more massive and the sand beds being thinner and less massive than those of the Oakville. This description is reasonably accurate in some areas of the outcrop and shallow subsurface where the Fleming is separated from the Oakville. (See sections I-I', J-J', and L-L', figs. 10, 11, and 13.) In other areas, the Fleming on the outcrop and in the shallow subsurface contains a ratio of sand to clay that approximates that of the Oakville. Where the Fleming Formation is not separated from the Oakville and directly overlies the Catahoula, from about Grimes County to the Sabine River, the percentage of sand in the formation increases eastward. In Jasper and Newton Counties, the amount of sand in the section above the base of the Fleming greatly exceeds the amount of clay. This can be seen in wells 30 and 31 on strike section L''-L''' (fig. 15).

Delineation of the base of the Fleming from the surface to the deep subsurface has not been attempted on most of the sections because of complex facies changes. In southeast Texas on sections A-A', B-B', and C-C' (figs. 2-4) an approximate base of the Fleming is shown downdip to short distances beyond the pinchout of the Anahuac. The preponderance of sand above the Anahuac in this area, however, makes any delineation on the basis of electrical logs speculative. Deep wells near the coastline penetrate marine facies of the Fleming which carry a diagnostic fauna. Numerous species, which serve to identify the formation, have been described by Rainwater (1964). *Potamides matsoni*, *Amphistegina sp.*, *Bigenerina humblei*, and *Bigenerina nodosaria var. directa* are faunal markers indicated on some of the sections.

### Post-Miocene

Delineation of the stratigraphic units of Pliocene, Pleistocene, and Holocene age has not been attempted. Correlation problems with most of these stratigraphic units are too numerous to solve by using only electrical logs. Delineation of the Pleistocene units--Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay--is exceedingly difficult due to the lithologic similarity of the sediments and lack of paleontological control. The contact at the surface of the basal Quaternary with the Goliad Sand or older units is, however, shown on the dip sections.

The Goliad Sand of Pliocene age overlies the Miocene units in the deep subsurface as well as in places on the surface. Except for a few isolated outcrops, it is otherwise entirely overlapped on the surface east of Lavaca County by Pleistocene deposits. Its inland extent beneath the overlap is presumed to be only several miles southeast from the most downdip exposures of the Fleming Formation. From Lavaca County to the Rio Grande, the width of the Goliad outcrop gradually increases because the Goliad progressively overlaps older units in the Rio Grande Embayment of south Texas.

The Goliad Sand can usually be identified on the surface and in the subsurface by a preponderance of sand except in the far eastern part of the State where sand predominates from the base of the Miocene to the surface. In this area, the identity of the Goliad cannot be established with certainty. Delineation of the base of the Goliad has been made, where outcrop control is available, on the strike and dip sections west of Colorado County. The base of the Goliad has been approximated at about 2,200 feet (671 m) below sea level near the coastline on sections I-I' and J-J' (figs. 10, 11).

## HYDROGEOLOGIC FRAMEWORK

The following discussion is restricted to the hydrogeologic framework of five units--Catahoula confining system (restricted), Jasper aquifer, Burkeville confining system, Evangeline aquifer, and Chicot aquifer. A discussion of other hydrologic units of Cenozoic age is beyond the purpose and scope of this report.

The quality of the ground water that is indicated on the sections to be less than 3,000 mg/L of dissolved solids is referred to in this report as fresh to slightly saline water. This terminology follows the classification of Winslow and Kister (1956).

## Catahoula Confining System (Restricted)

The Catahoula confining system (restricted) is treated in this report as a quasi-hydrologic unit with different boundaries in some areas than the stratigraphic unit of the same name. Its top (base of the Jasper aquifer) is delineated along lithologic boundaries that are time-stratigraphic in some places but that transgress time lines in other places. Its base, which coincides with the base of the stratigraphic unit, is delineated everywhere along time-stratigraphic boundaries that are independent of lithology. No attempt was made to establish a lithologic (hydrologic) base for the unit, which would have created a distinct hydrologic unit. Such effort would have involved a thorough hydrologic evaluation of pre-Miocene formations, which is beyond the scope of the project.

In many places, the Catahoula confining system (restricted) is identical to the stratigraphic unit, but there are notable exceptions. These departures of the hydrologic boundaries from the stratigraphic boundaries are most prominent in the eastern part of the Coastal Plain near the Sabine River (fig. 15), in places in south Texas (fig. 11), and in numerous places at the outcrop and in the shallow subsurface. In these places, the very sandy parts of the Catahoula Tuff or Sandstone (stratigraphic unit) that lie immediately below the Oakville Sandstone or Fleming Formation are included in the overlying Jasper aquifer. This leaves a lower section from 0 to 2,000 feet (610 m) or more in thickness that consists predominantly of clay or tuff with some interbedded sand to compose the Catahoula confining system (restricted). In most areas, this delineation creates a unit that is generally deficient in sand so as to preclude its classification in these areas as an aquifer. Thus in much of its subsurface extent, the Catahoula confining system (restricted) functions hydrologically as a confining layer that retards the interchange of water between the overlying Jasper aquifer and underlying aquifers.

The amount of clay and other fine-grained clastic material in the Catahoula confining system (restricted) generally increases downdip, until the Anahuac Formation is approached. Below this unit, the "Frio" Formation becomes characteristically sandy and contains highly saline water that extends to considerable depths.

## Jasper Aquifer

The Jasper aquifer, which was named by Wesselman (1967) for the town of Jasper in Jasper County, Texas, has heretofore not been delineated farther west than Washington, Austin, and Fort Bend Counties. In this report, a delineation as far downdip as possible has been made of the Jasper from the Sabine River to the Rio Grande.

The configuration of the Jasper aquifer in the subsurface, as shown on the sections, is geometrically irregular. This irregularity is due to the fact that the delineation was necessarily made on the basis of the aquifer being a rock-stratigraphic unit. The hydrologic boundaries were defined by observable physical (lithologic) features rather than by inferred geologic history.

The configuration of the base and top of the Jasper transgresses stratigraphic boundaries along strike and downdip. The lower boundary of the aquifer coincides with the stratigraphic lower boundary of the Oakville or Fleming in some places. In other places the base of the Jasper lies within the Catahoula or coincides with the base of that unit. The top of the aquifer is within the Fleming Formation in places, follows the top of the Oakville Sandstone in other places, and is within the Oakville in still other places.

The Jasper ranges in thickness from as little as 200 feet (61 m) to about 3,200 feet (975 m). The maximum thickness occurs within the region of highly saline water in the aquifer. An average range in thickness of the aquifer within the zone of fresh to slightly saline water is from about 600 to 1,000 feet (183 to 305 m). In the eastern part of the Coastal Plain of Texas the Jasper contains a greater percentage of sand than in the southern part. At the Sabine River, the Jasper attains a thickness of 2,400 feet (732 m) in well 31 on section L''-L''' (fig. 15), where the aquifer is composed almost entirely of sand. Fresh to slightly saline water, as shown on section D-D' (fig. 5), occurs as deep as 3,000 feet (914 m) below sea level.

Delineation of the Jasper aquifer in Louisiana (Whitfield, 1975), in western Louisiana and eastern Texas (Turcan, Wesselman, and Kilburn, 1966), and in Jasper and Newton Counties, Texas (Wesselman, 1967) shows that the thickness of the Jasper at the Sabine River closely approximates that given by the author. For example, the author assigns a thickness of 2,400 feet (732 m) to the Jasper in well 31 on section L''-L''' (fig. 15), and the authors cited above show essentially the same thickness at the site. This agreement in aquifer thickness, however, is contrasted to different interpretations of the stratigraphic composition or age of the aquifer near the Sabine River. The authors cited above restrict the Jasper to a part of the Fleming Formation, whereas this paper redefines the Jasper at its type locality near the Sabine River to include the upper part of the Catahoula of Texas in addition to the lower part of the Fleming of Texas. (This redefinition applies only to the area of the type locality and is thus only locally valid. Elsewhere in the Coastal Plain of Texas the Jasper assumes a different stratigraphic makeup.)

The stratigraphic discrepancies at the Texas-Louisiana border are attributed to different interpretations of the surface geology at the State line. The Palestine quadrangle of the Geologic Atlas of Texas (Barnes, 1968b) shows the Catahoula outcrop to be about 6 miles (9.7 km) wide at the Sabine River, whereas Welch (1942) shows the outcrop in Louisiana to be about 1 mile (1.6 km) wide. A close comparison of the two geologic maps indicates that in Louisiana the Lena, Carnahan Bayou, and at least part of the Dough Hills Members of Fisk (1940) of the Fleming Formation of Kennedy (1892), in addition to the Catahoula of Welch (1942), are equivalent to the Catahoula of Texas. Wesselman (1967) assigned the Carnahan Bayou Member as the basal part of the Jasper, which is reasonable; but this member is Catahoula in age in Texas. As long as the discrepancy in geologic mapping is unresolved, subsurface correlations of the Catahoula-Fleming contact, as well as formation thicknesses, will continue to differ.

## Burkeville Confining System

The Burkeville confining system, which was named by Wesselman (1967) for outcrops near the town of Burkeville in Newton County, Texas, is delineated on the sections from the Sabine River to near the Rio Grande. It separates the Jasper and Evangeline aquifers and serves to retard the interchange of water between the two aquifers.

The Burkeville has been mapped in this report as a rock-stratigraphic unit consisting predominantly of silt and clay. Boundaries were determined independently from time concepts although in some places the unit appears to possess approximately isochronous boundaries. In most places, however, this is not the case. For example, the entire thickness of sediment in the Burkeville confining system in some areas is younger than the entire thickness of sediment in the Burkeville in other places.

The configuration of the unit is highly irregular. Boundaries are not restricted to a single stratigraphic unit but transgress the Fleming-Oakville contact in many places. This is shown on sections D-D' to G-G' and J-J' (figs. 5-8 and 11). Where the Oakville Sandstone is present, the Burkeville crops out in the Fleming but dips gradually into the Oakville because of facies changes from sand to clay downdip.

The typical thickness of the Burkeville ranges from about 300 to 500 feet (91 to 152 m). However, thick sections of predominantly clay in Jackson and Calhoun Counties account for the Burkeville's gradual increase to its maximum thickness of more than 2,000 feet (610 m) as shown on section F-F' (fig. 7).

The Burkeville confining system should not be construed as a rock unit that is composed entirely of silt and clay. This is not typical of the unit, although examples of a predominance of silt and clay can be seen in some logs in sections H-H' and I-I' (figs. 9-10). In most places, the Burkeville is composed of many individual sand layers, which contain fresh to slightly saline water; but because of its relatively large percentage of silt and clay when compared to the underlying Jasper aquifer and overlying Evangeline, the Burkeville functions as a confining unit.

## Evangeline Aquifer

The Evangeline aquifer, which was named and defined by Jones (Jones, Turcan, and Skibitzke, 1954) for a ground-water reservoir in southwestern Louisiana, has been mapped also in Texas, but heretofore has been delineated no farther west than Washington, Austin, Fort Bend, and Brazoria Counties. Its presence as an aquifer and its hydrologic boundaries to the west have been a matter of speculation. D. G. Jorgensen, W. R. Meyer, and W. H. Sandeen of the U.S. Geological Survey (written commun., March 1, 1976) recently refined the delineation of the aquifer in previously mapped areas and continued its delineation to the Rio Grande. The boundaries of the Evangeline as they appear on the sections in this report are their determinations.

The Evangeline aquifer has been delineated in this report essentially as a rock-stratigraphic unit. Although the aquifer is composed of at least the Goliad Sand, the lower boundary transgresses time lines to include sections of sand in the Fleming Formation. The base of the Goliad Sand at the outcrop coincides with the base of the Evangeline only in south Texas as shown in sections H-H' to K-K' (figs. 9-12). Elsewhere, the Evangeline at the surface includes about half of the Fleming outcrop. The upper boundary of the Evangeline probably follows closely the top of the Goliad Sand where present, although this relationship is somewhat speculative.

The Evangeline aquifer is typically wedge shaped and has a high sand-clay ratio. Individual sand beds are characteristically tens of feet thick. Near the outcrop, the aquifer ranges in thickness from 400 to 1,000 feet (122 to 305 m), but near the coastline, where the top of the aquifer is about 1,000 feet (305 m) deep, its thickness averages about 2,000 feet (610 m). The Evangeline is noted for its abundance of good quality ground water and is considered one of the most prolific aquifers in the Texas Coastal Plain. Fresh to slightly saline water in the aquifer, however, is shown to extend to the coastline only in section J-J' (fig. 11).

## Chicot Aquifer

The Chicot aquifer, which was named and defined by Jones (Jones, Turcan, and Skibitzke, 1954) for a ground-water reservoir in southwestern Louisiana, is the youngest aquifer in the Coastal Plain of Texas. Over the years, the aquifer gradually was mapped westward from Louisiana into Texas where, heretofore, its most westerly mapped limit was Austin, Fort Bend, and Brazoria Counties. In this report, the delineation of the Chicot was refined in previously mapped areas and extended to near the Rio Grande by D. G. Jorgensen, W. R. Meyer, and W. M. Sandeen of the U.S. Geological Survey (written commun., March 1, 1976).

It is believed that the base of the Chicot in some areas has been delineated on the sections in this report as the base of the Pleistocene. Early work in southeast Texas indicates that the Chicot probably comprises the Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay of Pleistocene age and any overlying Holocene alluvium (table 1). The problem that arises in this regard is that the base of the Pleistocene is difficult to pick from electrical logs. Thus any delineation of the base of the Chicot in the subsurface as the base of the Pleistocene is automatically suspect. At the surface, the base of the Chicot on the sections has been picked at the most landward edge of the oldest undissected coastwise terrace of Quaternary age. In practice, the delineation of the Chicot in the subsurface, at least on the sections in southeast Texas, has been based on the presence of a higher sand-clay ratio in the Chicot than in the underlying Evangeline. In some places, a prominent clay layer was used as the boundary. Differences in hydraulic conductivity or water levels in some areas also served to differentiate the Chicot from the Evangeline.

The high percentage of sand in the Chicot in southeast Texas, where the aquifer is noted for its abundance of water, diminishes southwestward. Southwest of section G-G' (fig. 8) the higher clay content of the Chicot and the absence of fresh to slightly saline water in the unit is sharply contrasted with the underlying Evangeline aquifer that still retains relatively large amounts of sand and good quality water.

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**DAVIS, K.E., 1986**

**FACTORS AFFECTING THE AREA OF REVIEW FOR HAZARDOUS WASTE DISPOSAL WELLS**

# *PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON SUBSURFACE INJECTION OF LIQUID WASTES*

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# FACTORS EFFECTING THE AREA OF REVIEW

# FOR HAZARDOUS WASTE DISPOSAL WELLS

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## Abstract

The area of review, for a hazardous waste disposal well, is defined as the radial distance from the receiving well in which the pressure, caused by injection, increases sufficiently to possibly cause migration of fluids into useable sources of drinking water (USDW). Among the potential conduits for fluid migration from the disposal formation are improperly plugged well bores, channeling behind the casing of the injection w faulted formations, solution channels, naturally fractured formation facies pinch-outs. Usually faults, solution channels and most other naturally occurring geological conduits are filled with native fluids and are frequently sealed from USDWs by secondary mineralization. This paper concerns itself with only those conduits that are man-made.

Man-made conduits such as old abandoned test holes or oil and gas wells are sealed with cement plugs and drilling mud. The static mud column provides substantial resistance to upward flow. Most mud systems develop a gel structure when allowed to remain quiescent. To initiate flow up an improperly abandoned well bore, the pressure in the disposal zone must exceed the sum of the static mud column pressure and the mud gel strength pressure. If the sum of these values is not exceeded during the life of a hazardous waste disposal well, there is no potential for contamination of USDWs. This paper presents a simplified procedure which can be used to calculate that effected area.

## Introduction

The area of review, for a deep injection well, is determined by the zone of endangering influence for the life expectancy of that well. The zone of endangering influence is defined as that area the radius of which is the lateral distance in which pressures in the injection zone may cause the migration of the injection and/or formation fluid into an underg source of drinking water (USDW).

Factors affecting this area of review are the radial extent of ground water movement from the well bore, the rate of pressure build-up in the reservoir, through time, at various distances from the well bore and the potential for upward migration of fluids through man-made conduits.

The prediction of the probable rate of pressure increase and radial fluid movement in the disposal reservoir, resulting from the injection of fluids is a problem often confronted by injection well operators and regulatory agencies. Fluid injected into a formation which is already liquid filled will result in an increase in pressure in that formation. This injected fluid must be accommodated by either one or a combination of the following; expansion of the pore space in the matrix rock, compression of either or both the formation and injected fluids or expulsion of the formation water.

The resulting increase in pressure in the receiving formation due to the injection of fluids pose potential environmental threats to our USDWs if any man-made conduits exist within the area of review. Among the potential conduits for fluid migration from the disposal formation are improperly plugged well bores, channeling behind the casing of the injection well, faulted formations, solution channels, naturally fractured formations or facies pinch-outs.

## Factors Effecting the Area of Review

### Area of Review

The radius of the area of review for an injection well is determined either by calculating the zone of endangering influence or by using a fixed radius from the well bore which ever is less. The distance of the fixed radius varies from state to state. In states where the Environmental Protection Agency (EPA) has primacy, the fixed radius is 1/4 mile, while in primacy states or states that set their own regulatory standards so long as they meet or exceed EPA standards, the fixed radius varies from 1/4 mile to 2-1/2 miles.

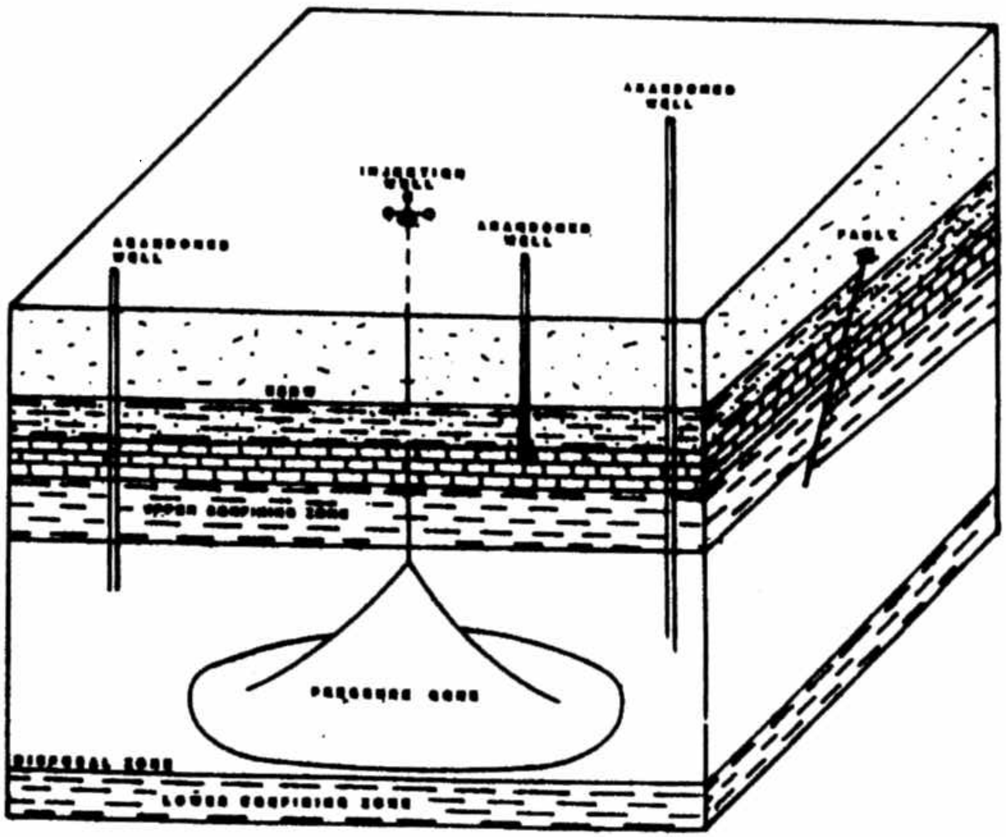
Computation of the zone of endangering influence should be calculated for an injection period equal to the expected life of the well. There are several equations that can be used for determining the area of review. The most notable and widely used is shown below (Barker, 1971; Ferris, et al, 1962; Kruseman and DeRidder, 1970; Lohman, 1972).

$$h = \frac{Q}{4\pi T}\left(-0.577216 - \log_e u + u - \ldots - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \ldots\right) \quad (1)$$

where

$$h = \frac{r^2 S}{4Tt}$$

FIGURE 1
SCHEMATIC SHOWING FACTORS
AFFECTING THE AREA OF REVIEW



and

$h$ = hydraulic head change at radius $r$ and time $t$
$Q$ = injection rate
$T$ = transmissivity
$S$ = storage coefficient
$t$ = time since injection began
$r$ = radial distance from well bore to point of interest.

For large values of time, small values of radius of investigation, or both, Equation 1 can be reduced to:

$$\Delta h = \frac{2.30Q}{4\pi T} \log \frac{2.25Tt}{r^2S} \quad (2)$$

Unfortunately, this equation does not address all the possible well configurations, multiple well systems, reservoir conditions, skin effects and other variables and combinations thereof. Warner, et al (1979) posed the use of several equations based on specific conditions of the system being evaluated. They indicated that an adequate approximation of the pressure build-up caused by injection into infinite confined reservoirs can be determined if we assume

1. Flow is horizontal.
2. Gravity effects are negligible.
3. The reservoir is homogeneous and isotropic.
4. The injected and reservoir fluids have a small and constant compressibility.
5. The receiving reservoir is infinite in areal extent and is completely confined above and below by impermeable beds.
6. Prior to injection the piezometric surface in the vicinity of the well is horizontal, or nearly so.
7. The volume of fluid in the well is small enough so that the effect of the wellbore can be neglected.
8. The injected fluid is taken into storage instantaneously. That is, pressure effects are transmitted instantaneously through the aquifer.

The basic differential equation for the unsteady radial flow of a slightly compressible fluid from an injection or other type well is (Matthews and Russell, 1967)

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\phi uc}{k}\frac{\partial P}{\partial t} \quad (3)$$

where:

| Symbol | Parameter or Variable | Practical Units |
|---|---|---|
| c | compressibility | $psi^{-1}$ |
| Q | porosity | decimal fraction |
| h | reservoir thickness | feet (ft) |
| k | permeability | millidarcies (m) |
| u | viscosity | centipoise (cp) |

| | | |
|---|---|---|
| p | pressure | psi |
| q | flow rate | stock tank barrels/day (STB/I |
| r | radial distance | feet (ft) |
| t | time | days (D) |

The pressure build-up equations used by Warner, et al (1979) wer written using dimensionless pressure ($P_D$) and dimensionless time ($t_D$). These dimensionless quantities are groups of variables that commonly occu in build-up equations and can be conveniently replaced by a single term Dimensionless time, for the units listed above is:

$$t_D = \frac{6.33 \times 10^{-3} kt}{\phi \mu c r^2} \tag{4}$$

In unsteady state or transient flow equations, dimensionles pressure ($P_D$) is a function of dimensionless time and, perhaps, othe quantities, depending on the particular buildup solution. It is define for each equation in which it is used, throughout the Warner report.

The Warner equations presented all contain the variable $\beta$, th formation volume factor, which is the ratio of the volume of the flui being injected at reservoir pressure compared with the volume a standard conditions (520°R, 14.7 psi). For liquids, $\beta$ can, fo practical purposes, be considered to be 1.0, as in all examples in thi report. However, $\beta$ is quite variable when the injected fluid is gas When a highly compressible fluid is being injected, $\beta$ should b evaluated at an average reservoir pressure. In cases where the pr ur is not known, enter a value of $\beta = 1.0$, obtain the approximate pre then evaluate $\beta$ (Amyx, et al, 1960) and recalculate the pressure.

## Multiple Well Effects

As indicated in Figure 2, if we assume a constant injection rate fo a single well penetrating the entire receiving aquifer, and adjust fo practical units, the differential equation, Equation 3, has a solution o the form

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} [Ei \left(\frac{39.5 \phi\mu c r^2}{kt}\right)] \tag{5}$$

and for the case where $1/t_d < 0.01$. This is approximated as

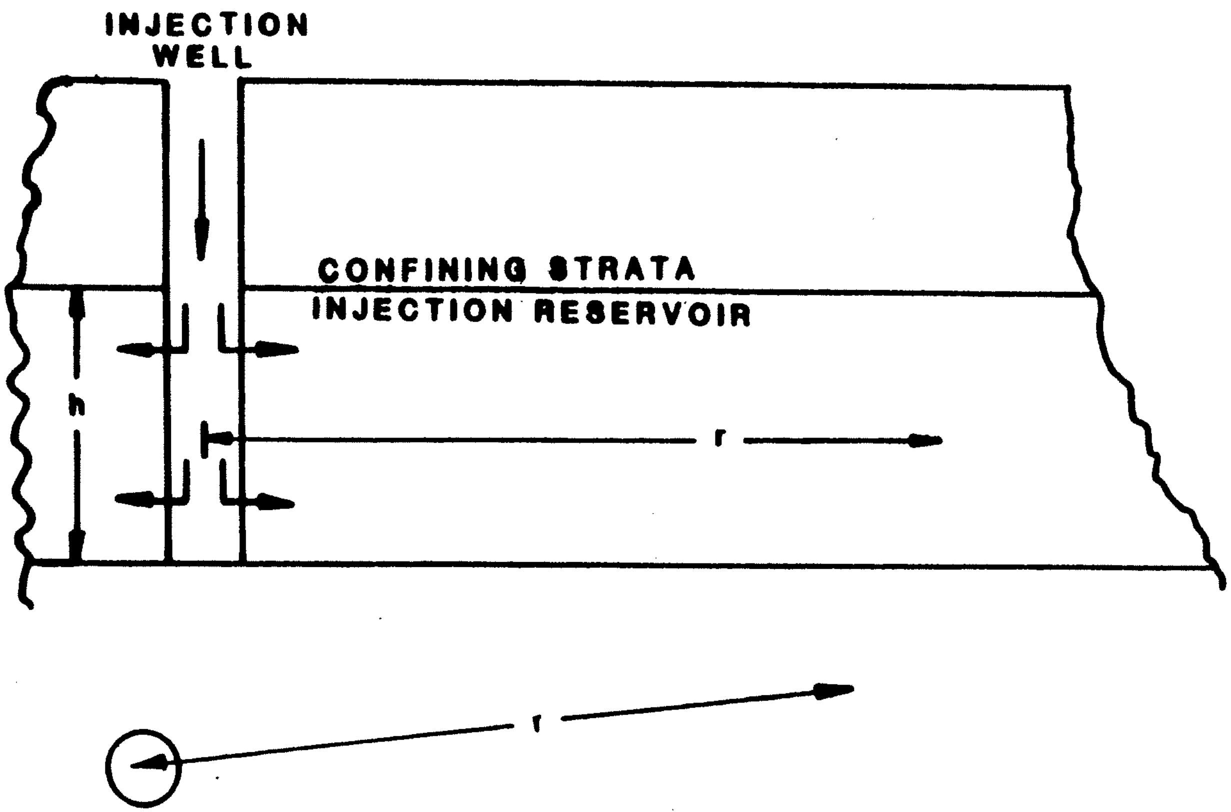
$$P_r = P_i + 162.6 \frac{q\mu\beta}{kh} \log\left(\frac{kt}{70.4 \phi\mu c r^2}\right) \tag{6}$$

where

FIGURE 2

PROFILE AND PLAN VIEWS OF A COMPLETELY PENETRATING WELL INJECTING INTO A CONFINED RESERVOIR. PRESSURE IS TO BE CALCULATED AT A POINT r DISTANCE FROM THE WELL.

(FROM WARNER, et.al. 1979)



| Symbol | Parameter of Variable | Practical Units |
|---|---|---|
| $\beta$ | formation volume factor | Std Stk Tank BBL (RB/STB) |
| $P_r$ | reservoir pressure at radius r | psi |
| $P_i$ | initial reservoir pressure | psi |

A convenient characteristic of these equations (Warner, 1979) is that the effects of individual wells can be superimposed to obtain the combined effect of multiple wells. As indicated in Figure 3, the pressure at any given point in a reservoir can be evaluated by summing the pressures caused by each of the individual injection wells. Assuming the same criteria as in Equations 4 and 5 above, except for multiple wells, we have

$$P_r = P_i + 70.6 \left[ \sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} Ei \left( \frac{39.5\ \phi_n \mu_n c_n r_n^2}{k_n t_n} \right) \right] \quad (7)$$

where n is the well number.

For cases where $1/t_d < 0.01$, an adequate approximation is

$$P_r = P_i + 162.6 \left[ \sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \log \left( \frac{k_n t_n}{70.4\ \phi_n \mu_n c_n r_n^2} \right) \right] \quad (8)$$

If we assume a variable injection rate for the same criteria as previously applied, the applicable equation is

$$P_r = P_i + 70.6 \left[ \sum_{a=1}^{n} \frac{(q_a - q_{a-1}) \mu \beta}{kh} Ei \left( \frac{39.5\ \phi \mu c r^2}{k(t - t_{a-1})} \right) \right] \quad (9)$$

For cases where $1/t_d < 0.01$

$$P_r = P_i + 162.6 \left[ \sum_{a=1}^{n} \frac{(q_a - q_{a-1}) \mu \beta}{kh} \log \left( \frac{k(t - t_{a-1})}{70.4\ \phi \mu c r^2} \right) \right] \quad (10)$$

where a is the time interval under consideration and $q_a$ is the rate during that time interval.

These equations are based on the principle of superposition. That is, the pressure effects begin with the initial injection period $t_1$ and rate $q_1$. When a new rate $q_2$ is implemented, it is as if a new well begins to operate at that rate, with the effects superimposed on the original well, while the original well continues to operate at rate $q_1$. This performance is shown diagrammatically in Figure 4.

FIGURE 3

PROFILE AND PLAN VIEWS OF TWO COMPLETELY PENETRATING WELLS INJECTING INTO A CONFINED RESERVOIR. PRESSURE IS TO BE CALCULATED AT A POINT AT RADII $r_1$ AND $r_2$ FROM WELLS 1 AND 2 RESPECTIVELY.

( FROM WARNER, et.al. 1979)

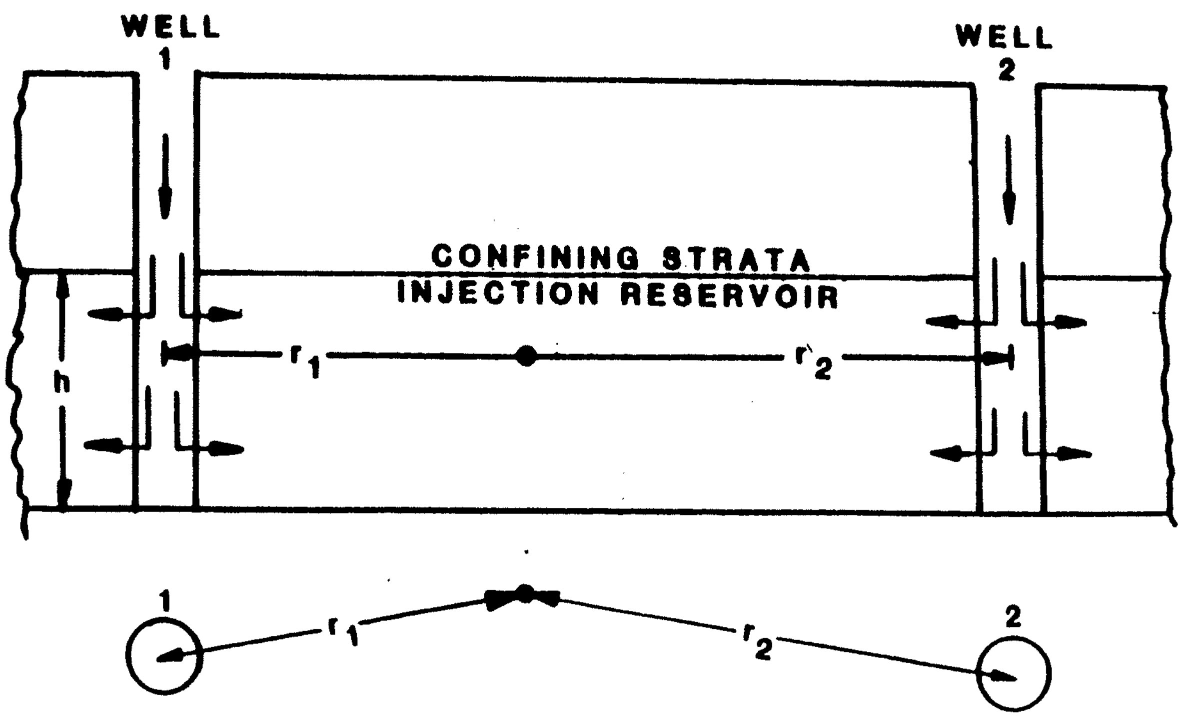
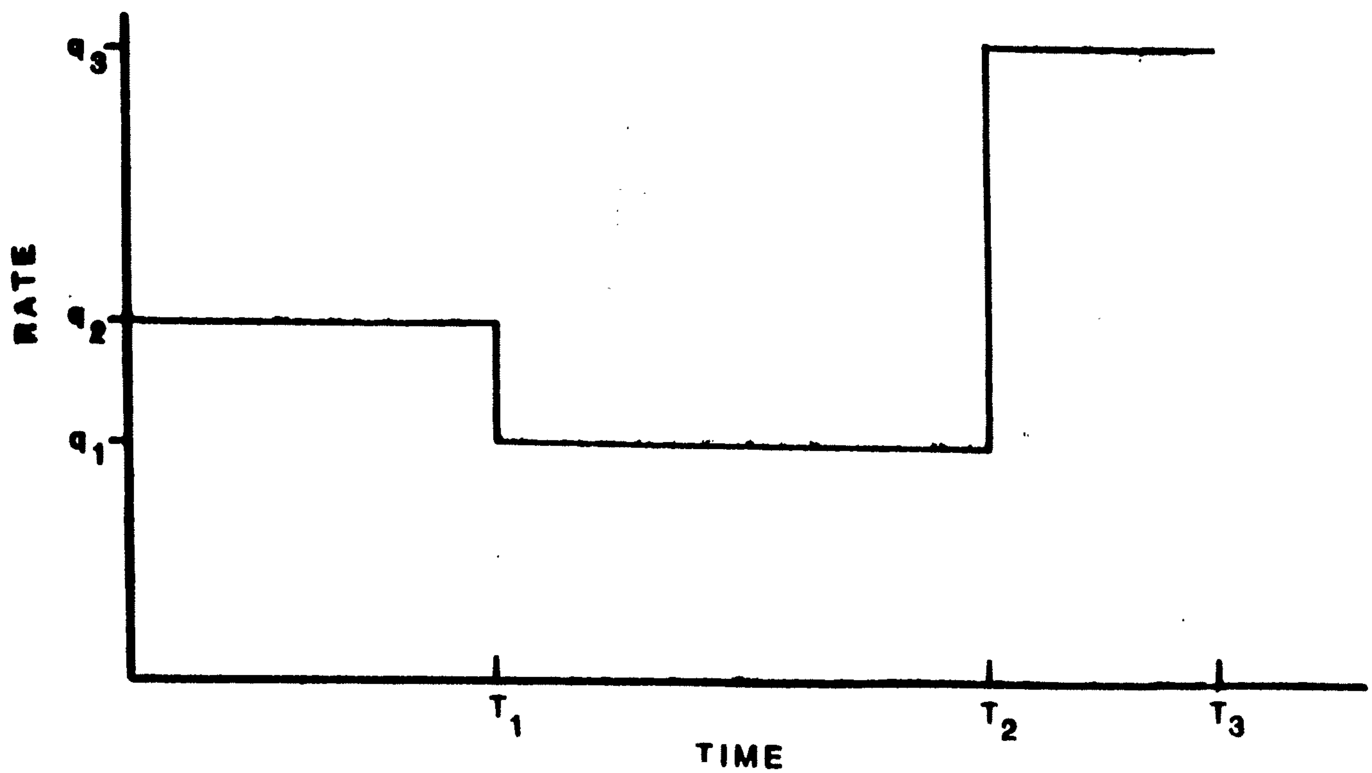


FIGURE 4

DIAGRAMMATIC REPRESENTATION OF THE INJECTION HISTORY OF AN INJECTION WELL OPERATING AT A VARIABLE RATE,
(FROM WARNER, et.al. 1979)



In computing the pressure buildup caused by multiple injection wells operating at variable rates, the principle of superposition is applied twice, once for computation of the pressure effects of each well and a second time in summing the effects of the individual wells. Figure 2 depicts two wells whose effects must be summed and Figure 3 shows a possible pattern of variable rate injection that might exist.

The applicable equation is:

$$P_r = P_i + \left[ \sum_{b=1}^{m} \sum_{a=1}^{n} \frac{70.6(q_{ba} - q_{b(a-1)})}{k_b h_b} \, Ei \left( \frac{39.5 \phi_b \mu_b c_b r_b^2}{k_b (t_b - t_{b(a-1)})} \right) \right] \qquad (11)$$

Where b is the well number, a is the time interval under consideration for well b, and $q_{ba}$ is the rate for well b during time interval a. For cases where $1/t_d < 0.01$, an adequate approximation is:

$$P_r = P_i + \left[ \sum_{b=1}^{m} \sum_{a=1}^{n} \frac{162.6(q_{ba} - q_{b(a-1)})}{k_b h_b} \, \log \left( \frac{k_b (t_b - t_{b(a-1)})}{70.4 \phi_b \mu_b c_b r_b^2} \right) \right] \qquad (12)$$

In summary, these two equations state and perform the calculation for each well, as done for the single-well variable-rate case and then sum the effects of the wells.

## Skin Effects

Warner, et. al. (1979) also addressed the effects of skin damage. Injection wells may suffer permeability loss in the vicinity of the wellbore during construction or operation or they may experience permeability gain. Permeability loss can result from drilling mud invasion, clay-mineral reactions, chemical reactions between injected and aquifer water, bacterial growth, etc. Permeability gain can result from chemical treatment such as acidization or from hydraulic fracturing and other mechanical stimulation methods. These permeability changes, which occur in the immediate vicinity of the wellbore are called "skin effects" by the petroleum industry and are described by a "skin factor" (van Everdingen, 1953; Hurst, 1953). The skin factor (s) is positive for permeability loss and negative for permeability gain.

The skin factor can vary from about -5 for a hydraulically fractured well to + $\infty$ for a well that is completely plugged (Earlougher, 1977). The incremental pressure difference caused by the skin effect is described by:

$$\Delta P_s = s \frac{q}{2\pi kh} \qquad (13)$$

Equation 13 is applied by combining it with equations that are derived for pressure buildup without skin effects. For example, Equation 5 is rewritten below to include skin effects:

$$P_r = P_i + \frac{70.6q\mu\beta}{kh} [Ei\left(\frac{39.5\phi\mu cr^2}{kt}\right) + 2s] \quad (14)$$

When $1/t_d < 0.01$, an adequate approximation of Equation 14 is:

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} [\ln\left(\frac{kt}{70.4\phi\mu cr^2}\right) + 2s] \quad (15)$$

Equations 14 and 15 are only valid at the wellbore. No equations ar presented here for calculation of pressure buildup near the wellbore, i the zone of damage or improvement, because this zone is relatively thi and because the calculations are of relatively limited applicaton Outside of the skin zone, the standard equations can be applied with n correction (Earlougher, 1977). The thickness of the skin is determined b (Hawkins, 1956):

$$r_s = r_w e^{s\ k_s/k-k_s} \quad (16)$$

Seldom if ever, will $k_s$ be known. Reasonable estimates of k can, however, be made to allow calculation of the range of possible ski thicknesses. Consideration of the sources of permeability reductio around a wellbore indicates that, in the case of wellbore damage, r would seldom be greater than a few feet. The radius of permeabilit improvement can be greater, in the tens of feet for an ordinary hydrauli fracturing program, but probably less than 100 feet as the maximum $r_s$ except in cases of massive hydraulic fracturing.

It should be noted that these equations can only be used for pre buildup at the well. As discussed above, s is assumed to be zero and th ordinary buildup equations should be applied for points outside of th skin zone, which is estimated by Equation 16 or assumed to be less tha 100 feet, if Equation 16 can not be used.

It is generally assumed, in estimating the pressure effects o injection wells, that the wells will be drilled completely through th injection reservoir. This will usually be true, since it maximizes th injection efficiency of the well. However, for mechanical or geologica reasons, drilling is sometimes stopped before complete penetration of th reservoir has been achieved. Such wells are described as partiall penetrating. In other cases, a well may be drilled completely through reservoir, but only a part of the reservoir is completed for injectio Figure 5 depicts partially penetrating and partially completed wells. Th equation for pressure buildup as a result of injection into (pumping fro such a well (Hantush, 1964; Witherspoon, et al, 1967) is:

$$P_r = P_i + P_{DPP}\left(\frac{141.2q\mu\beta}{\phi\mu cr^2}\right) \quad (17)$$

where:

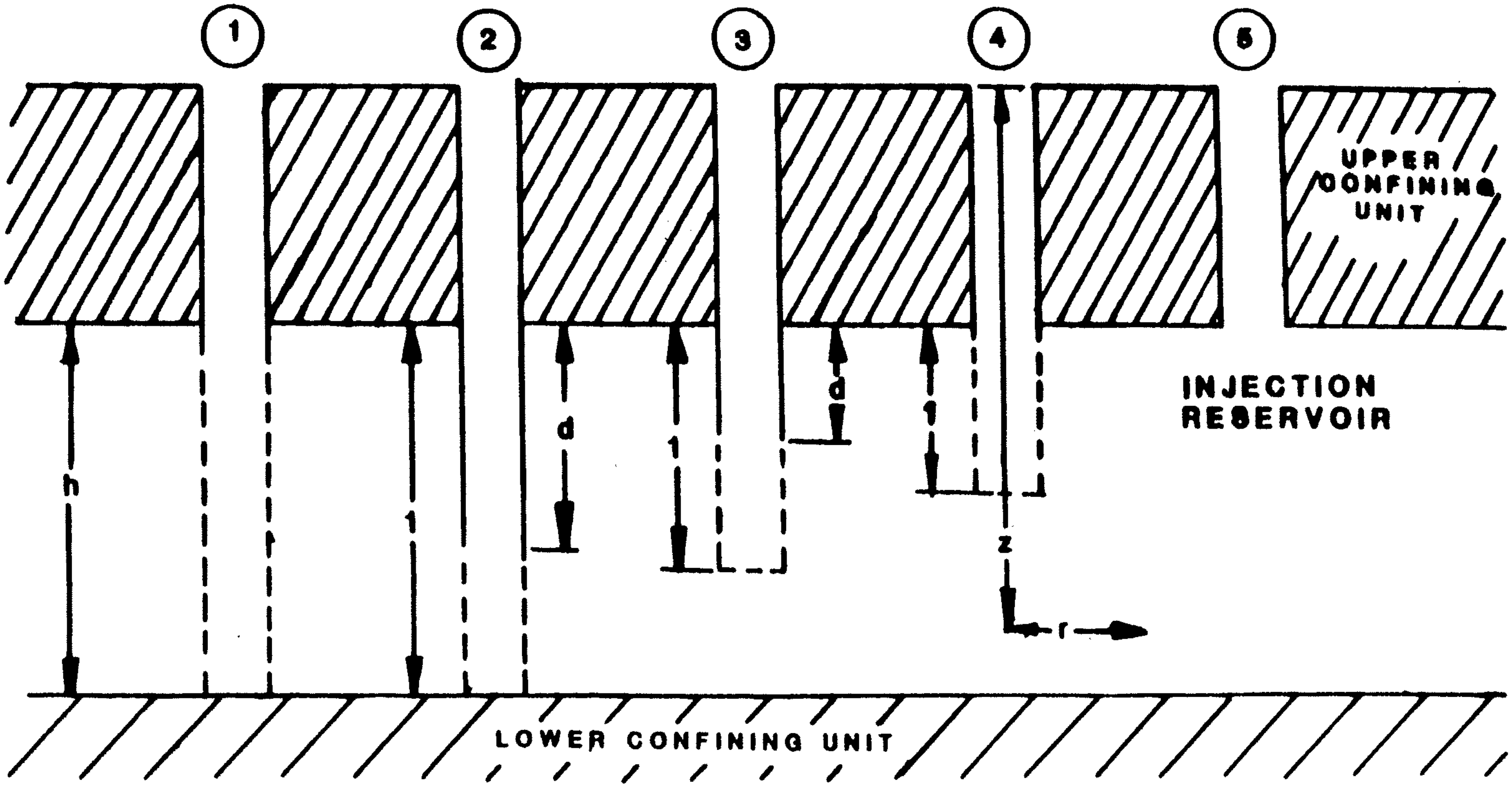
$$P_{DPP} = \frac{1}{2} [Ei \left(\frac{1}{4t_D}\right) + f(r, h, l, d, z)]$$

FIGURE 5

WELLS WITH VARYING DEGREES OF PENETRATION AND COMPLETION

1. FULLY PENETRATING FULLY COMPLETED WELL.
2. FULLY PENETRATING PARTIALLY COMPLETED WELL.
3. PARTIALLY PENETRATING PARTIALLY COMPLETED WELL.
4. PARTIALLY PENETRATING FULLY COMPLETED WELL.
5 NON-PENETRATING WELL.

(FROM WARNER, et.al. 1979)



Partial penetration results in greater pressure buildup (decline) a and near the wellbore than would be experienced in a fully penetr--ir well for the same injection (pumping) rate. The magnitude of diff depends on the degree of penetration, l; the ratio of the radiu investigation to aquifer thickness, r/h; the length of the complete interval, l-d; and the vertical point of investigation, z. The expande form of Equation 17 is too complex for practical use by hand and th number of variables so large that is is impractical to provide tables fo evaluation of $P_{DPP}$. Computer programs have been developed to solv Equation 17 by Warner, et al (1979).

Warner, et al (1979) also addressed the effects of fracture reservoirs, infinite semiconfined reservoirs, bounded reservoirs reservoirs with variable permeability, reservoirs with radially varyin permeability and fluids of variable viscosity. Although all thes possibilities may effect pressure buildup within a reservoir an therefore, the area of review, their specific values are rarely known Normally these values can only be determined through well testin utilizing pressure buildup and fall off or step rate injection testing Reasonable estimates can normally be made with the aforementione equations and adjusted for these parameters after operating the system fo a reasonable period of time.

## Criteria for Eliminating Potential USDW Contamination through Geologica Barriers

### Geohydrological Factors

Several geohydrological factors must be considered when studying th area of review for deep well injection. The subsurface environment is complex physical and chemical system. Before the injection of fluids int this system can be permitted, it must be evaluated for its ability t contain the wastes. Upward migration of wastes can occur through eithe natural geologic or man-made pathways. Natural geologic conduits such a faults, solution channels or fractures are usually filled with nati fluids and are frequently sealed from USDWs by secondary mineralizatior Man-made conduits such as old abandoned test holes or oil and gas well are sealed with cement plugs and drilling muds. However, the chemica effects of the injected waste on the formation rock and conduits, if any must also be evaluated. When evaluating these phenomena, we must remembe that chemical reactions in the subsurface are normally very slow ar equilibrium is reached very quickly. Since fluid movement in th subsurface is very slow, diffusion is the primary mixing factor ar provides additional support to waste containment near the well bore. we consider all the rocks that are commonly penetrated when a well drilled, the rock most susceptible to blocking both artificial and natura conduits is shale. Both sandstones and carbonate rocks can becor unstable, and fill a well bore or annular space when subjected to tecton stresses or when the hydrostatic mud pressure is lower than the pressu on the fluids within the rocks, particularly when the permeability is lo The instability of shale, on the other hand, is compounded t extraordinary manner that this rock is affected when exposed to wat

## Reaction of Shales and Clays

Shales are essentially rocks that contain clay. Shale rocks are formed by the compaction of sediments. Water is squeezed out as sediments are buried deeper by layers deposited progressively during geologic time. The degree of compaction of the sediments is proportional to the depth of burial, provided the water is able to escape easily to permeable strata. The younger sediments soften and disperse when mixed with water. The older shales usually have undergone diagenesis, may remain hard and are less easily dispersed into water. The term shale is applied to everything from clays to lithified materials such as slate. Soft clays are extremely reactive with water while slates are relatively inert. Because the various shales behave differently upon exposure to drilling fluids when penetrated by the bit, it is useful to classify shales so that instability may be approached in a somewhat systematic manner. Such a classification is shown in Table I.

The amount of clay, the type of clay, the depth of burial, and the amount of water in a given shale all relate to the stability of the shale. The amount of clay in a given shale depends on the composition of the shale sediments at the time of deposition. The type of clay in a given shale depends not only on sediment composition at the time of deposition, but also on changes that may occur in the clay after burial.

From the view point of effect on hole stability, clays may be classified broadly as expandable and non-expandable. Expandable clays exhibit a high degree of swelling when wetted with water. Expandable clays as a group are called smectites. Montmorillonite (bentonite) is a high-swelling member of the smectite group. The non-expandable clay most commonly found in shales is illite. Chlorite and kaolinite are non-expandable clays often found in shales as well. Non-expandable clays swell much less than expandable clayes on being wetted with water. The degree of swelling of both clay types varies greatly with the type and amount of salt dissolved in the water with which the clay is wetted (R.E. Grim, 1968).

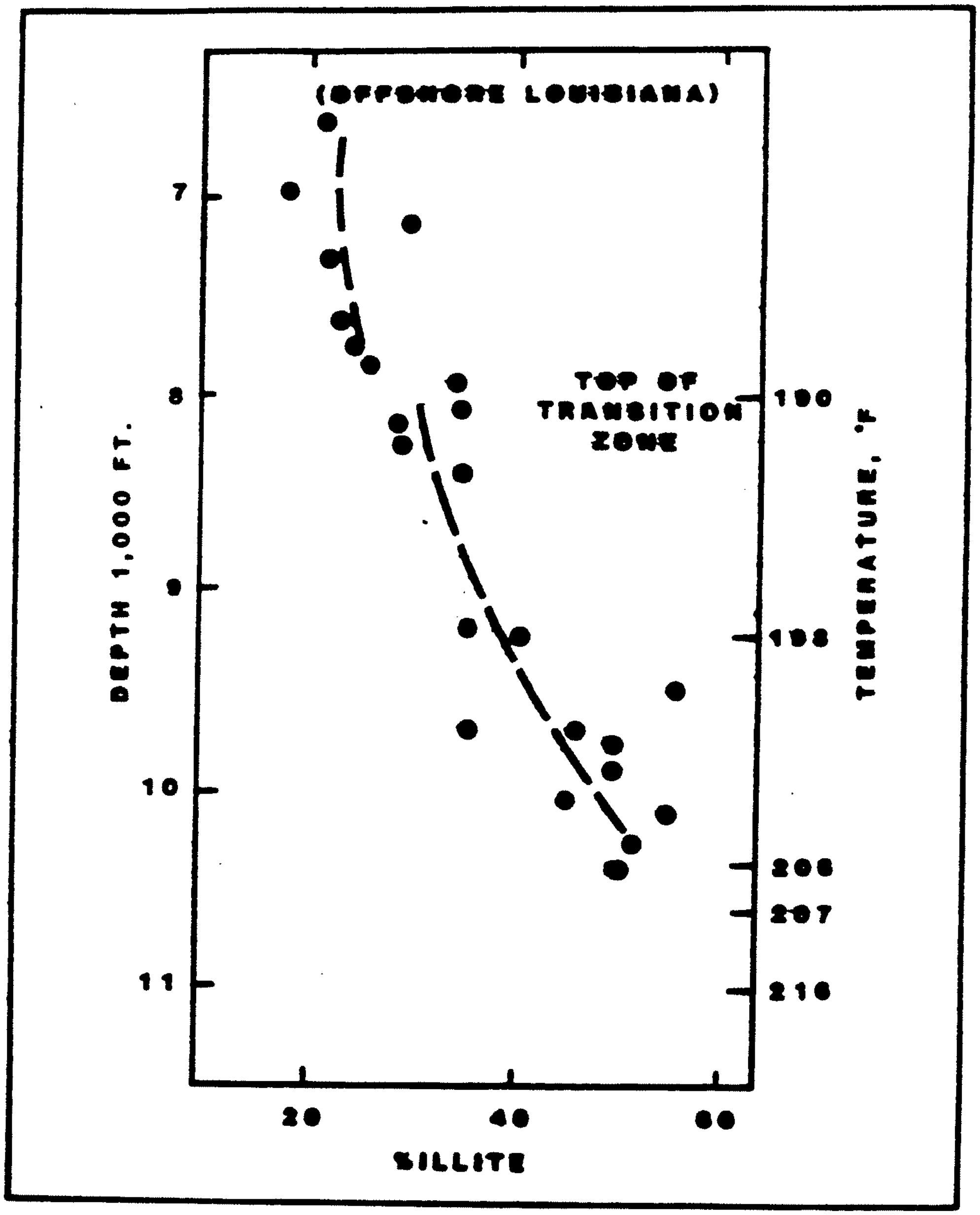
The type of clay in younger sediments depends in large part on the temperature at depth of burial. A change in clay mineralogy with depth is illustrated in Figure 6 (W.H. Fertl and D.J. Timko, 1970). The increasing percentage of illite with depth is attributable to alteration of smectite to illite. The alteration phenomenon is called "diagenesis". Some water of crystallization is released from the expandable clay during diagenesis. Illite differs from montmorillonite structurally in that some of the silicons in the outer silicate layers (R.E Grim, 1968) of illite are always replaced by aluminums, and the resultant charge deficiency is balanced by potassium ions (R.E. Grim, 1968). Temperature, rather than pressure, is thought to be the critical variable in the reaction through which this change is brought about.

The amount of water in a given shale depends on the depth of burial and the type of clay in the shale. Loosely bound water is squeezed out of the shale by pressure exerted by the weight of the overburden of the earth at depth of burial. A good approximation of the magnitide of overburden pressure is 1 psi/ft of depth. A laboratory experiement that illustrates

FIGURE 6

**LATTICE MIXING**

(FROM FERTLAND AND TIMKO)



this phenomenon is presented graphically in Figure 7 (H.C.H. Darley, 1969). Both bentonites in this illustration are expandable clays, and the Ventura shale contains mostly non-expandable clays. Most of the free water that can be easily squeezed out of the expandable clays is freed with a effective pressure of 2500 to 2000 psi. A matrix (grain to grain) stress of this magnitude would be expected in the crust of the earth at a depth of about 4500 to 5500 feet. Additional water is released as the swelling clays are subjected to even greater effective pressures.

## Causes of Shale Instability

Shale instability may result from the following forces, either singly or in combination:

1. Overburden pressure
2. Pore pressure
3. Tectonic forces
4. Water adsorption
    a. Dispersion
    b. Swelling

Various forms of hole instability arise when the stress relief of overburden pressure occasioned by drilling exceeds the yield strength of the formation. A well-known example of this phenomenon is the plastic flow that occurs in geopressured shales. The water content and the plasticity of the shale are abnormally high relative to the overburden load, and the shale is extruded into the hole in plastic flow.

When the pressure of the drilling fluid is less than the pressure of the fluids within the pores of the rock being drilled, the pressure differential toward the hole tends to induce fragments of rock to fall into the hole. Such caving is more likely to occur when the rock is relatively impermeable. The strength of the rock is a factor in this process as well.

Tectonic forces result from stresses imposed on a given stratum by deformation of the crust of the earth. Such deformation is commonly described as folding and faulting, and is a normal result of the formation of mountains. Stresses thus created are relieved quickly in shale that is readily deformable, but tend to remain in rocks that are brittle. Even a small amount of water adsorption can cause sufficient stress to induce shales to flake off in fragments and slough into the hole.

## Shale Classifications

Reference to a shale classification like the one given in Table I is helpful for a description of the effect of water absorption on shale stability. Because the number of combinations of physical and chemical properties of rocks called "shale" is so large, a classification of some kind is necessary for a logical and organized approach to predict the probability of occurrence. For purposes of illustration, a description follows of how shales of Class A through E behave upon wetting with fresh water. Obviously the behavior of the different classes of shale would be different in various salt solutions.

FIGURE 7

WATER RETAINED UDER LOAD

(FROM DARLEY)

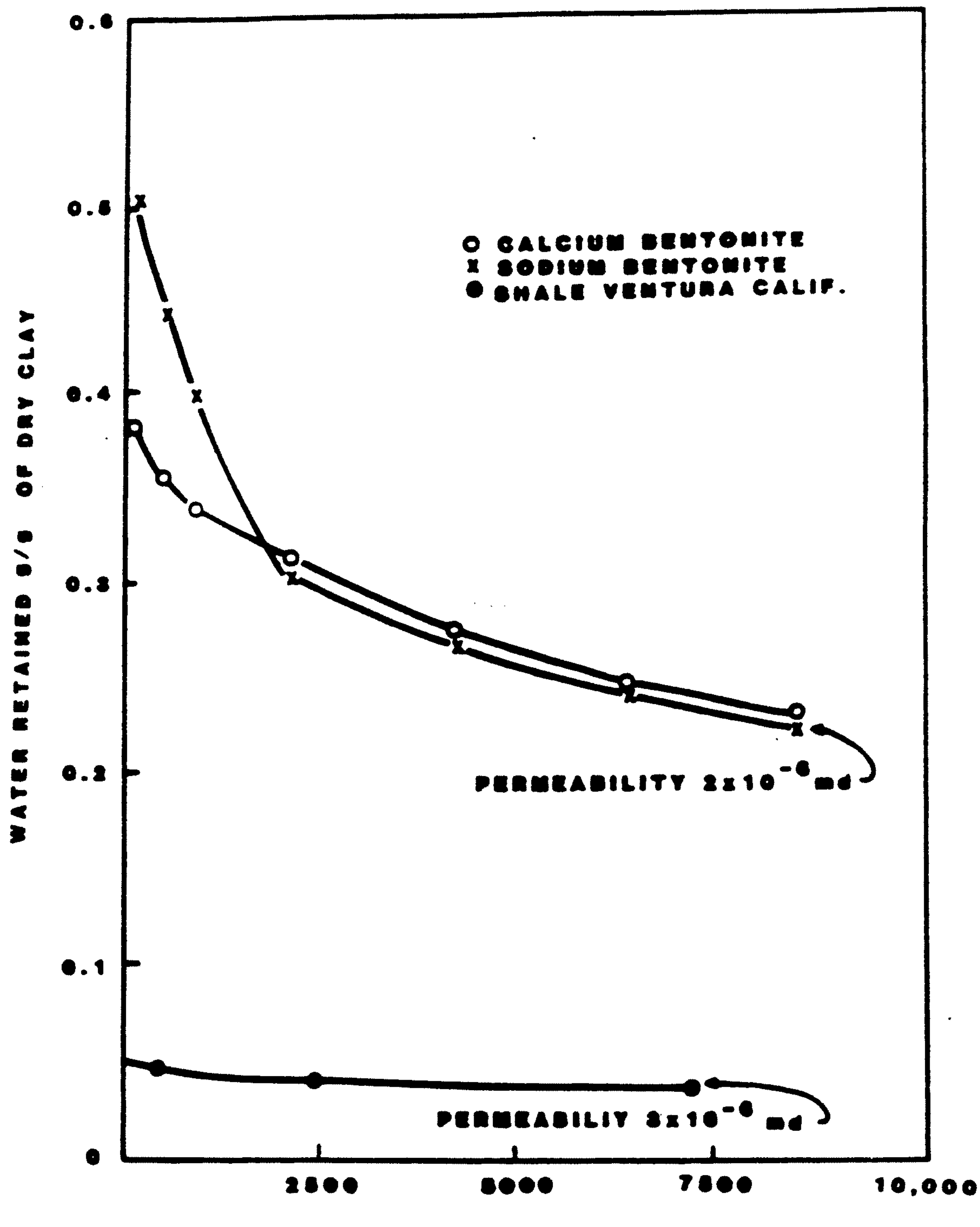


TABLE 1

A GENERAL SHALE CLASSIFICATION

| Class | Texture | Methylene blue capacity (me/100g) | Water Content | Wt% Water | Clay Content | Wt% Clay | Density g/cc |
|---|---|---|---|---|---|---|---|
| A | Soft | 20-40 | Free and bound | 25-70 | Montmorillonite and illite | 20-30 | 1.2-1.5 |
| B | Firm | 10-20 | Bound | 15-25 | Illite and mixed layer montmorillonite-illite | 20-30 | 1.5-2.2 |
| C | Hard | 3-10 | Bound | 5-15 | Trace of montmorillonite high in illite | 20-30 | 2.2-2.5 |
| D | Brittle | 0-3 | Bound | 2-5 | Illite, kaolin chlorite | 5-30 | 2.5-2.7 |
| E | Firm-hard | 10-20 | Bound | 2-10 | Illite and mixed layer montmorillonite-illite | 20-30 | 2.3-2.7 |

(From Mondshine 1969)

Class-A shale is characterized primarily by high-water content an relatively high expandable clay content. The word montmorillonite as use in Table I denotes expandable clays as identified by the methylene test. The word smectite is now a more widely accepted group Montmorillonite is a member of the smectite group. Shale of this qua..t is often found at shallow depth where the overburden load is still to small to have squeezed more water from the sediments during compaction and the temperature too low to have induced diagenesis. The same shal may also be found at greater depth when permeable avenues for the escap of connate water did not exist, and where conditions were not right fo montmorillonite to have been altered to illite (see Figure 6). When stil more water is added to Class A shale, it would be expected that th compaction process would be to a degree reversed. In the higher wate content range, this shale could also be squeezed into the hole from th pressure created by the weight of the overburden. The lower the mu weight, the more likely it would be for this phenomenon to occur.

Class-B shale would respond to adsorption of fresh water mainly b becoming more plastic or less firm. Water would penetrate slowly from th borehole into the shale body. Capillary adsorption of water into beddin planes would occur nominally if at all, because of the smectite clays i the shale. Abnormal pore pressure in shale of this description i possible. Aside from possible pressure effects, Class-B shale woul usually remain rather stable after being penetrated.

Class-C shale would be more likely to slough into the hole tha either Class A or B. This type of shale would be found in sediment similar to those that constituted Class-B shale, but at greater d Some softening would occur upon adsorption of fresh water. Very l there would be sections where the shale would still be hard after wate adsorption and some swelling, so that some fragments would disengage fro the matrix and fall into the hole. The mechanism of fragmentation coul be the result of either capillary adsorption along bedding planes, o simply penetration of water into the shale body away from the hole.

Class D shale may be found at both shallow and great depths, but i likely to be quite old geologically. Brittle shale subdivides into smal particles when immersed in water, but swells and softens very little if a all. It is believed that cleavage takes place along old fracture plane that are held together by attractive forces that act over short distance only. Hydration when contacted by an aqueous drilling fluid cause separation at the old fracture planes.

Class E shales are likely to be found quite deep, and are usuall abnormally pressured. Occurrence of this type of shale is sometime thought to be anomalous, even though it is found quite often in sediment of tertiary age. This shale would have a strong tendency to slough upo adsorption of fresh water. In interbedded smectite-illite intervals illite ledges may be borken off by the unequal degree of swelling of th two different shales.

## Shale Hydration

Water wetting of shale can and usually does result in borehole blockage. The instability usually results primarily from overburden pressure, pore pressure, or tectonic stress. This is true regardless or whether the clay in the shale is largely expandable or non-expandable, or whether the shale in place is brittle or plastic. Moreover, shale disperson, hole closure or sloughing from shale swelling are all attributable to adsorption of water by shale.

The forces that cause shale to absorb water are attributable to the clay in the shale. It should also be emphasized at the outset that these forces through which clay adsorbs, imbibes, draws or sucks water into itself can be very great. By comparison the force with which mud filtrate may be pressed into the formation by the differential between the hydrostatic pressure of the mud column and the pore pressure of the formation is very small. For example, if a normally pressured stratum at 5000 or 10,000 feet on the Gulf Coast is drilled with 9.5 ppg mud, the pressure differential would be about 125 and 250 psi respectively. This figure represents the pressure with which filtrate from the mud is being pressed into the formatio by the overbalance of hydrostatic pressure over pore pressure. The text following will illustrate that the water adsorption forces of shale are much greater.

Hydration of shale depends upon a number of factors such as the hydration energy of the interlayer cations on the clays present and the charge density on the surface of the clay crystals. A reasonable estimate of the shale hydration force can be made by considering the compaction forces involved in subsurface burial of a given shale stratum during geologic time. For well drilling purposes, the hydration force is calculated conveniently in this way. The effective compaction stress on a shale section at any given depth can be represented by the equation, $s = S - P$, where s is the intergranular or matrix stress (W.R. Mathews and J. Kelly, 1967), S is the overburden pressure (approximately 1 psi/ft), and P is the pressure on the fluid in the pores of the rock.

As a given layer of shale is buried deeper, progressively more water is squeezed out of the shale by the weight of the overburden. The force with which water is being expelled from the shale in the compaction process equals the intergranular or matrix stress. The adsorption (or suction) force of the clay acts in opposition to the water expulsion force of compaction. This compacting force is relieved on the borehole face when the shale is penetrated by the bit. Consequently, a hydration force equal to the degree of relief develops. Since the compaction force equals the matrix stress, then:

$$\text{SHALE HYDRATION FORCE}_{psi} = \text{OVERBURDEN}_{psi} - \text{PORE PRESSURE}_{psi}$$

For example, assuming again a normally pressured shale (9 lb/gal mud weight equivalent) at 10,000 ft on the Gulf Coast:

$$\text{OVERBURDEN}_{psi} = 1 \text{ psi/ft} = 10{,}000 \text{ psi}$$

$$\begin{aligned}\text{MATRIX STRESS}_{psi} &= \text{OVERBURDEN}_{psi} - \text{PORE PRESSURE}_{psi} \\ &= 10{,}000 \text{ psi} - (9 \times 0.052 \times 10{,}000) \text{ psi} \\ &= 5320 \text{ psi}\end{aligned}$$

The shale hydration force at 10,000 feet in normal pore pressure is therefore 5320 psi.

Drilling Fluids

Artificial penetrations in the area of review or zone of endangering influence can provide potential conduits to USDWs if improperly plugged when abandoned, improperly cemented when constructed or a combination thereof. Artificial penetrations are usually man-made holes used for the exploration of oil and gas or other minerals and water. These holes are rarely empty and are fluid filled with native water, brine or drilling fluid. In the case of native waters or brine the fluids may have seeped into the well bore or been left there by the original driller. If the well was originally drilled with a cable tool rig or rotary drilling rig using compressed air, the fluid in the hole is probably native water or brine. However, the vast majority of artificial penetrations are made exploring for oil and gas. Therefore, it is logical to conclude that most well bores are mud filled since rotary drilling techniques using drilling fluid are predominately used when drilling oil and gas exploration and development wells. Upon completion of the drilling operation, if the well is not completed for production, the drill pipe is removed from the bore and the drilling mud used to drill the well will remain in the bore indefinitely. If the well is completed or casing is run and partially cemented across a portion of the well bore, drilling mud would have been displaced ahead of the cement from the annular space between the casing and open hole. If cement was not circulated to the surface, then the annular space above the cemented section will be filled with drilling mud.

A fluid filled well bore or annular space provides resistance to upwards fluid migration because of two opposing forces. The first would be the hydrostatic head or downward force caused by the weight of the fluid column. This can be described as psi/foot of depth by taking the weight of one cubic foot of water and dividing it into 144 square inches one-foot high. A cubic foot of water weighs approximately 62.3 pounds dividing by 144 square inches, we find that a column of water one-foot high exerts a downward pressure of 0.433 psi. Therefore a column of water 1000 feet deep would provide a downward force of 433 psi. If fluid were migrating upward, it would have to have a driving force in excess of 433 psi. This example used fresh water having a density of 8.33 lbs/gal. The second opposing force that would act as a deterent to fluid migration along a well bore would be present only if the fluid filling the well bore had gel strength. Most drilling fluids contain this characteristic.

One of the primary functions of the drilling mud is the removal of drilled cuttings from the well bore. The mud carries the cuttings from beneath the bit, transports them up the well bore/drill pipe annulus and releases them at the surface. Since normal drilling operations require that mud circulation be stopped periodically to add another joint of drill pipe, the mud must have a property which acts to suspend the drilled cuttings in the static mud column. This property is known as gel strength. Gel strength is time dependent and increases as the mud column remains quiescent. Most drilling fluids are thixotropic and develop a gel structure like "Jello" when allowed to stand quiescent but become fluid when disturbed.

To determine the combined effect of both hydrostatic head and gel strength acting as a deterrent to fluid migration along a mud filled well bore or annulus, we must first identify the forces acting on a well bore and/or annulus existing in a static state. Figure 8 represents a vertical force diagram of a static mud column in an abandoned well that contains no uncemented casing. Figure 9 represents the forces acting on the static mud column in the annulus between the casing and open hole above the cemented interval.

The equation for the force balance in Figure 8 takes the following form,

$$w + GS_w(2\pi r_w h) = P_f(\pi r_w^2) - P_t(\pi r_w^2) \quad (18)$$

where

$$w = r_w^2 \rho h$$

and

$w$ = weight of mud column
$GS_w$ = gel strength of mud column acting on circumference area of well bore
$P_t$ = pressure at top of well
$P_f$ = pressure at formation being contained
$r_w$ = radius of well bore
$h$ = height of mud column in well bore
$\rho$ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

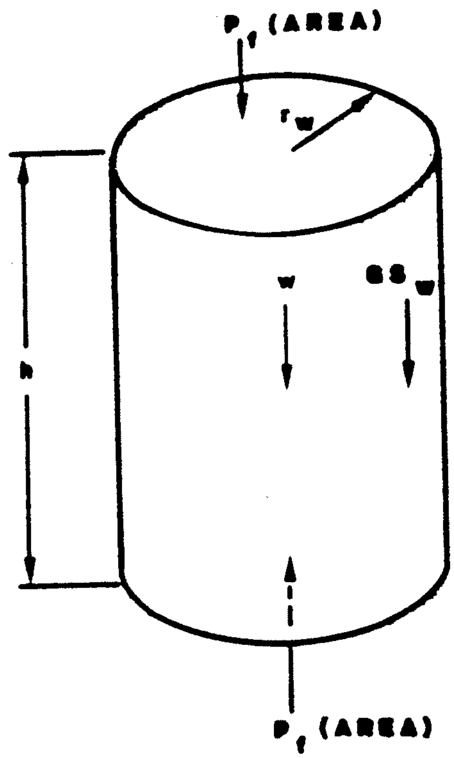
$$P_f = P_t + 0.052\rho h + 3.33 \times 10^{-3} GSh/D \quad (19)$$

where:

$P_f$ = pressure at the contained formation in psi
$P_t$ = pressure at the top of well
$\rho$ = density of mud in lb/gal
$h$ = height of mud column in feet
$GS$ = gel strength in lb/100 ft$^2$
$D$ = diameter of well bore in inches

FIGURE 8

STATIC MUD COLUMN
FORCE BALANCE DIAGRAM




$P_t$ (AREA) = PRESSURE AT THE TOP OF WELL = $P_t \pi r_w^2$

W = WEIGHT OF FLUID COLUMN $\rho h \pi r_w^2$

$GS_w$ = GEL STRENGTH OF MUD A ON CIRCUMFERENCE AREA OF WELL BORE = $GS_w (2\pi r_w h)$

$P_f$ (AREA) PRESSURE AT THE FORMATION BEING CONTAINED $P_f \pi r_w^2$

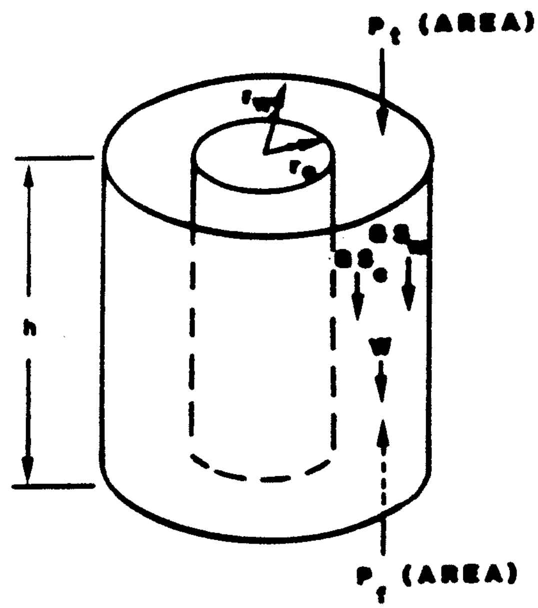
FORCES FROM MUD COLUMN SUM OF PRESSURE FORCES

$$W + GS_w (2\pi r_w h) = P_f (\pi r_w^2) - P_t (\pi r_w^2)$$

FIGURE 9

ANNULUS STATIC MUD COLUMN
FORCE BALANCE DIAGRAM

WELLBORE ANNULAR EFFECTS




FORCES FROM MUD COLUMN = SUM OF PRESSURE FORCE

$$W + GS_c(2\pi r_e h) + GS_w(2\pi r_w h) = P_f \pi(r_w^2 - r_e^2) - P_t \pi(r_w^2 - r_c^2)$$

The force balance equation for Figure 2 takes the form

$$w + GS_c(2\pi r_c h) + GS_w(2\pi r_w h) = P_f\pi(r^2_w - r^2_c) - P_t\pi(r^2_w - r^2_c) \qquad (20)$$

where

$$w = \rho h(r^2_w - r^2_c)$$

and

- $w$ = weight of mud column in annulus
- $GS$ = gel strength of mud acting on circumference area of both the well bore ($GS_w$) and casing wall ($GS_c$) and $GS_w = GS_c$
- $P_t$ = pressure at top of well
- $P_f$ = pressure at formation being contained
- $r_w$ = radius of well bore
- $r_c$ = outside radius of casing
- $h$ = height of mud column in annulus
- $\rho$ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

$$P_f = P_t + .\text{[illegible]}\rho h + \frac{3.33 \times 10_{-3} GSh}{D_w - D_c} \qquad (21)$$

where:

- $P_f$ = pressure at the contained formation in psi
- $P_t$ = pressure at the top of the well
- $\rho$ = density of mud in lb/gal
- $h$ = height mud column in feet
- $GS$ = gel strength of mud in lb/100 $ft^2$
- $D_w$ = diameter of well bore in inches
- $D_c$ = outside diameter of casing in inches

## Drilling Fluid Properties

It is generally recommended that the values required to calculate the flow resistance of a mud filled well bore or annular space be obtained from the well records. The physical configuration of the well can usually be obtained from many sources. These include but are not limited to state and federal permit records, the owner/operator files, commercial libraries, geological surveys and other public information sources. The density of the drilling fluid used to drill the well is normally recorded on the geophysical log heading as shown in Exhibit 1. The gel strength values may be more difficult to obtain. Mud properties are generally run while conditioning the mud to run casing and cement. These values are normally determined by the drilling fluid supplier or service company and are reported on standardized forms such as the one shown in Exhibit 2. These data are normally available from the owner/operator's well fi[illegible] o[illegible] the service company. Also, it is frequently not necessary to fin[illegible]

**EXHIBIT 1**

Schlumberger

# BOREHOLE GEOMETRY LOG

COUNTY
FIELD or LOCATION
WELL
COMPANY

COMPANY ____________________

WELL ____________________

FIELD ____________________

COUNTY ____________ STATE ____________

LOCATION

Sec. ______ Twp. ______ Rge. ______

Other Services:

Permanent Datum: ____________, Elev. ______

Log Measured From ______, ______ Ft. Above Perm. Datum

Drilling Measured From ______

Elev.: K.B. ______
D.F. ______
G.L. ______

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | |
| Run No. | | | | | | | | |
| Depth—Driller | | | | | | | | |
| Depth—Logger | | | | | | | | |
| Btm. Log Interval | | | | | | | | |
| Top Log Interval | | | | | | | | |
| Casing—Driller | @ | | @ | | @ | | @ | |
| Casing—Logger | | | | | | | | |
| Bit Size | | | | | | | | |
| Type Fluid in Hole | | | | | | | | |
| Fluid Level | | | | | | | | |
| Dens. Visc. | | | | | | | | |
| pH Fluid Loss | | ml | | ml | | ml | | ml |
| Source of Sample | | | | | | | | |
| $R_m$ @ Meas. Temp. | @ | °F | @ | °F | @ | °F | @ | °F |
| $R_{mf}$ @ Meas. Temp. | @ | °F | @ | °F | @ | °F | @ | °F |
| $R_{mc}$ @ Meas. Temp. | @ | °F | @ | °F | @ | °F | @ | °F |
| Source: $R_{mf}$ $R_{mc}$ | | | | | | | | |
| $R_m$ @ BHT | @ | °F | @ | °F | @ | °F | @ | °F |
| Time Since Circ. | | | | | | | | |
| Max. Rec. Temp. | | °F | | °F | | °F | | °F |
| Equip. Location | | | | | | | | |
| Recorded By | | | | | | | | |
| Witnessed By | | | | | | | | |

EXHIBIT 2

WELL HISTORY

Magcobar

| | | | |
|---|---|---|---|
| 1 | T20S | R36E | Salt Gel- Brine[illegible] |
| Lea | | | 7/29/80 |
| New Mexico | | | |

| | | | |
|---|---|---|---|
| 8 5/8 | 1204 | 12¼ | 1 |
| 7 | 3750 | 8 3/4 | 3 |

| DATE | DEPTH | MUD WT | VIS | FLOW LINE TEMP | PV | YP | GELS 0/10 | pH | API FILTRATE | HTHP FILTRATE | Pf | Mf | CHLORIDES | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | Materials | | | | | | | | DAILY COST | TOTAL MUD COST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1980 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3/1 DRILLING | 1090 | 8.8 | 30 | | | | | 9 | | | | | 2000 | Good | 8 | | | | | 10 | | | 2 | 1 | [illegible] | [illegible] | 314.96 | 314.96 |
| 3/3 DRILLING | 1977 | 10.3 | 30 | | | | | 8.3 | | | .1 | .8 | 150,000 | Good | 9 | | | | | 3 | | | 2 | 16 | | | 243.81 | 558.77 |
| 3/4 DRILLING | 2906 | 10.3 | 30 | | | | | 9 | | | .2 | 1 | 160,000 | Good | 3 | | | | | | | | | | | | -0- | 550.7 |
| 3/5 DRILLING | 3202 | 10.3 | 30 | | | | | 9 | | | .2 | 1 | 160,000 | Good | 3 | | | | | | | | | | | | -0- | 550.7 |
| 3/6 DRILLING | 3543 | 10.3 | 30 | | | | | 9 | | | .2 | 1 | 160,000 | Good | 3 | | | | | | | | 10 | | | | [illegible] | 862.0 |
| 3/7 LOGGING | 3750 | 10.3 | 30 | | 6 | 3 | 2/3 | 9 | 15 | | .2 | .8 | 160,000 | Good | 3 | | | | | | | | 10 | | 110 | [illegible] | 1737.27 | 2600.1 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | TOTAL [illegible] COST | | 3244.5 |

well records of each well since wells drilled adjacent to each other frequently use the same or similar mud systems. Historical records are also a good source of obtaining conservative values for gel strengths of specific types of drilling fluid systems.

Since the gel strength of different types of mud systems varies, it is difficult to determine the exact gel strength of the mud in a particular well bore. A review of the gel strength characteristics of various types of muds was made to evaluate the factors that effect the gel strength structure. The aim of this review was to provide sufficient information to determine the minimum gel strength structure that could be anticipated for any combination of formation, well bore and mud type. This value can then be used if insufficient data is available for a specific well bore.

Thixotropy is the property, exhibited by certain gels, of liquifying when stirred or shaken and then returning to their gelled state when allowed to stand quiescent. This property in drilling fluids is the result of various clay minerals being used as additives in drilling fluids. Generally, clay particles fall into the colloidal particle range. Colloidal systems used in drilling fluids include solids dispersed in liquids and liquid droplets dispersed in other liquids. These highly active colloidal particles comprise a small percentage of the total solids in drilling muds but act to form the dispersed gel forming phase of the mud that provides the desired viscosity, thixotropy and wall cake properties.

Clay particles and organic colloids comprise the two classes of colloids used when mixing drilling fluids. The common organic colloids include starch, carboxycelluloses and polyacrylomine derivatives.

Barker (1981) reported that, "The clay colloids utilized in common drilling fluids are characterized by a crystalline structure which influences the ability of the clay to retain water." Clays used in fresh water muds consist of hydrated alumnosilicates comprised of alternate plates of silica and aluminum to form layers of each mineral. The plate-like crystals have two distinct surfaces: a flat face surface and an edge surface. Slight surface polarities induce weak electrostatic forces along the faces and edges of the mineral plates. Garison (1939) noted that these electrostatic forces attract planer water to the colloidal particles forcing the clays to swell when wet and shrink when dry. The attraction of planer water to the faces of the plates is greater than the attraction of the sheets for each other therefore the structure tends to swell due to the absorbsion of the planer water from the drilling fluid. The bentonite clays demonstrate a strong ability to attract planer water as a result they experience extreme swelling. When in contact with fresh water, the face to face attraction of water by the mineral layers will continue until the swelling reduces the attraction of the plates to the point where they separate. This separation results in a higher number of particles and is referred to as dispersion. The dispersion causes the colloidal suspension to thicken. The degree of thickening depends on the electrolytic content, salt concentration of the water, time, temperature, pressure, pH, the exchangeable cations on the clay, and the clay concentration.

## Gel Strength, The Measure of Thixotropy

Thixotropy is essentially a surface phenomenon which is characte by gel strength measurements. The gel strength indicates the attr forces between particles under static conditions. The strength of th structure which forms under static conditions is a function of the amou and type of clays in suspension, time, temperature, pressure, Ph, and t chemical treating agents used in the mud. Those factors which promot the edge-to-edge and face-to-edge association of the clay particl defined as flocculation increase the gelling tendency of the mud and tho factors which prevent the association decrease the gelling tendency.

Due to their size, colloidal particles remain indefinitely suspension. When suspended in pure water the clay particles will n flocculate. When flocculation occurs the particles form clumps or floc These loosely associated flocs contain large volumes of water. If t clay concentration in the mud is sufficiently high, flocculation wi cause formation of a continuous gel structure instead of individu flocs.

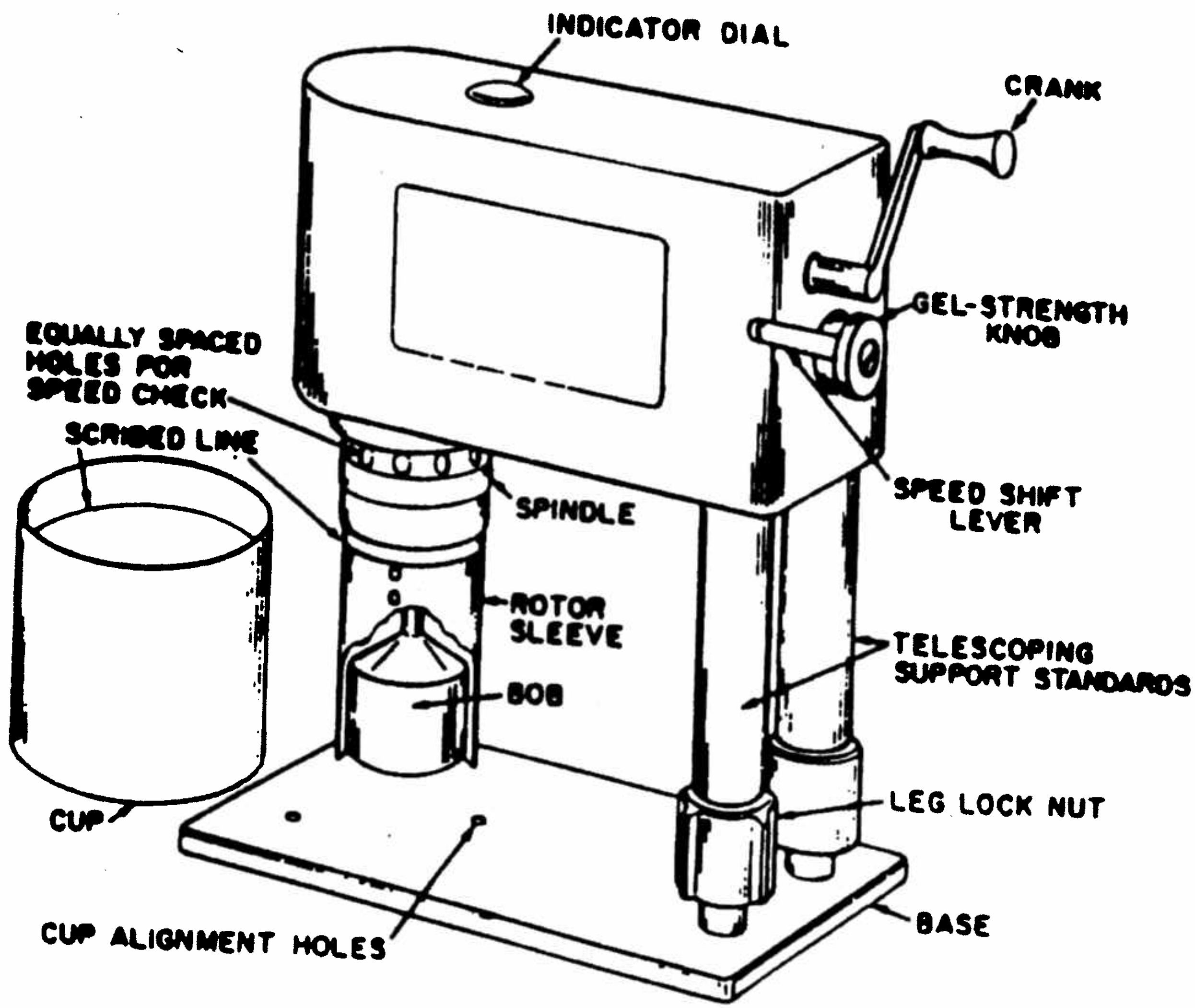
The gel structure commonly observed in aqueous drilling flui results from salt contamination. Soluable salts are usually present sufficient quantities to cause at least a mild flocculation. The ti required for the gel to attain an ultimate strength depends on t critical concentration of electrolyte required to initiate flocculatio the thinners present, and the concentration of the clay and of the sa present. During drilling the presence of salts and clay particles vari with each formation being drilled, therefore the drilling fl monitored and adjustments are made in order to maintain the desi strength.

## Gel Strength of the Static Mud Column

Gel strength is measured by a multispeed direct indicating viscome (See Exhibit 3) by slowly turning the driving shaft by hand and observ the maximum deflections before the gel structure breaks. The gel stren is normally measured after quiescent periods of 10 seconds (initial strength) and 10 minutes. The measurements are taken at surf conditions of standard temperature and pressure. To determine the strength of the static mud column in an abandoned well it is necessary determine the gel strength of the mud under the influence of boreh conditions. The initial and 10 minute gel strengths bare to dir relation to the ultimate gel strength of the mud at borehole conditio To determine the ultimate gel strength of a mud it is necessary to disc the factors which act to influence the initial gel strength at boreh conditions.

Once the drilling operation is completed and the well is aband the mud is subjected to conditions vastly different from those encount at the surface. In the range of formation depths utilized for disposa industrial wastes the temperature would be expected to range from 8( 300°F, the pressure from 1500 to 5000 psi and time from days to sev years. Several studies have been conducted to determine the i time, temperature and pressure on the gel strength of muds at

EXHIBIT 3
HAND VISCOMETER



conditions. The information obtained from this research should provid means of determining a reasonable minimum gel strength value for abandoned wells which exist in the range of formations described at

It is observed that common use water base muds develop high strengths after prolonged periods of quiescence. The relationship betw gel strength and time varies widely from mud to mud, depending on composition, degree of flocculation, temperature, pH, solids, pressure. Figure 10 (G.D. Gray, H.C. Darley and W.F. Rogers, 19 indicates the increase in gel strength with time for various mud types reveals that there is no well established means of predicting long t gel strengths with time. It is noted in all cases that the gel stren is observed to increase.

Garrison (1939) studied the gel strength in relation to time and r of reaction for California bentonites. He observed that both the sp and the final strength increased with the bentonite percentages. gelling was found to follow the equation:

$$S = \frac{S'kt}{1+kt} \tag{22}$$

where S is the gel strength at any time t, S' is the ultimate strength, and k is the gel rate constant. Figure 11 indicates that gel strength forms more rapidly at first then gradually approaches ultimate value as time elapsed. Equation 22 may be rewritten as:

$$\frac{t}{S} = \frac{t}{S'} + \frac{1}{S'k}$$

which indicates that a plot of t/S verses t should be a straight li Figure 11 represents the graph of t/S versus t, and indicates the slope the line is k and the y-intercept is 1/S'k. This approach provides means to evaluate the ultimate gel strength for each benton concentration. Table 2 represents the ultimate gel strengths and r constants for the five samples shown in Figures 11 and 12. Garrison a made measurements on similar suspensions at higher pH and determined t the ultimate strengths of the bentonite gels increased with e suspension as the pH increases. Table 3 reflects the pH - ultimate strength relationship observed.

Garrison also noted that the treating of muds with thinners had effect of decreasing the rate of gelling but not the ultimate strength. Thus it can be concluded that the reduced initial and 10 min gel strength will not be any less than that recorded for an untrea sample of the same mud. In fact, the ultimate gel strength may e increase as indicated in Table 2.

Garrison's work does not indicate that all muds comply with Equat 22, but it does point out that the initial and 10 minute gel strengths not provide a reliable means of predicting the ultimate gel s[illegible]ng Weintritt and Hughes (1965) conducted progressive gel strength

FIGURE 10

INCREASE IN GEL STRENGTH OF
VARIOUS MUD TYPES WITH TIME
(FROM GRAY, DARLEY, AND ROGERS)

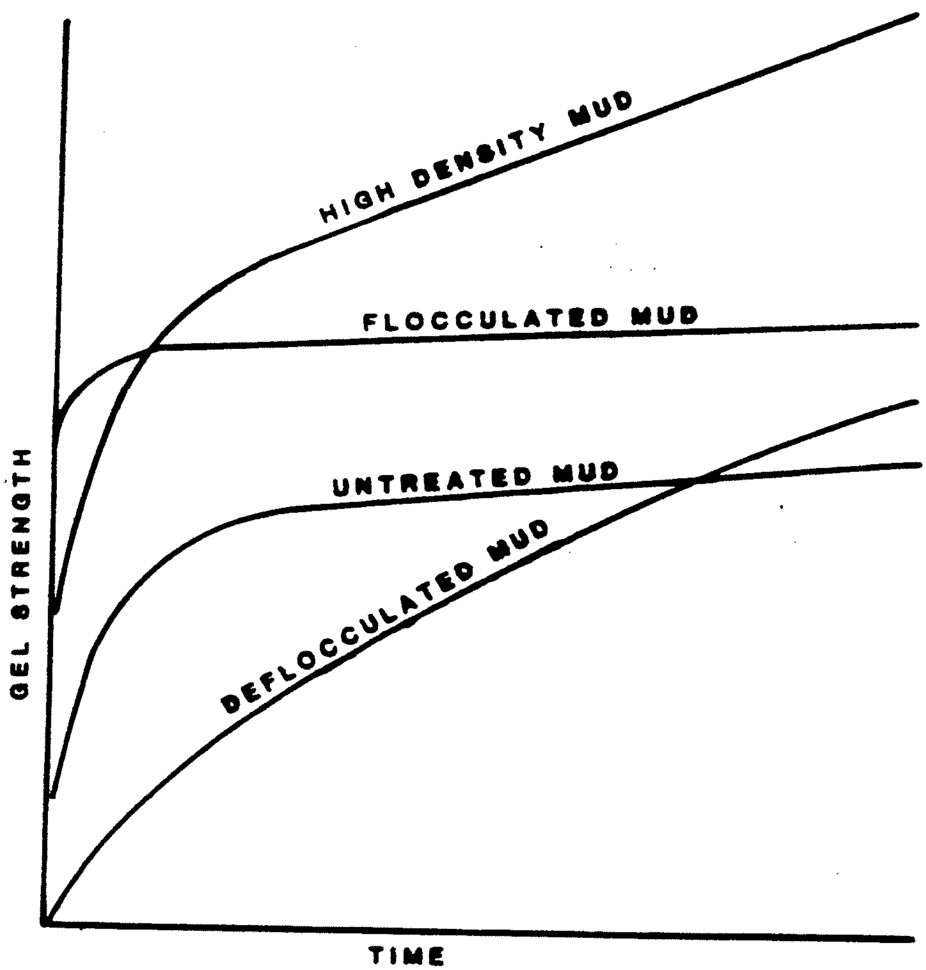


FIGURE 11
GEL STRENGTH IN RELATION TO TIME
AND RATE OF REACTION
(FROM GARRISON 1939)

SEE TABLE 2

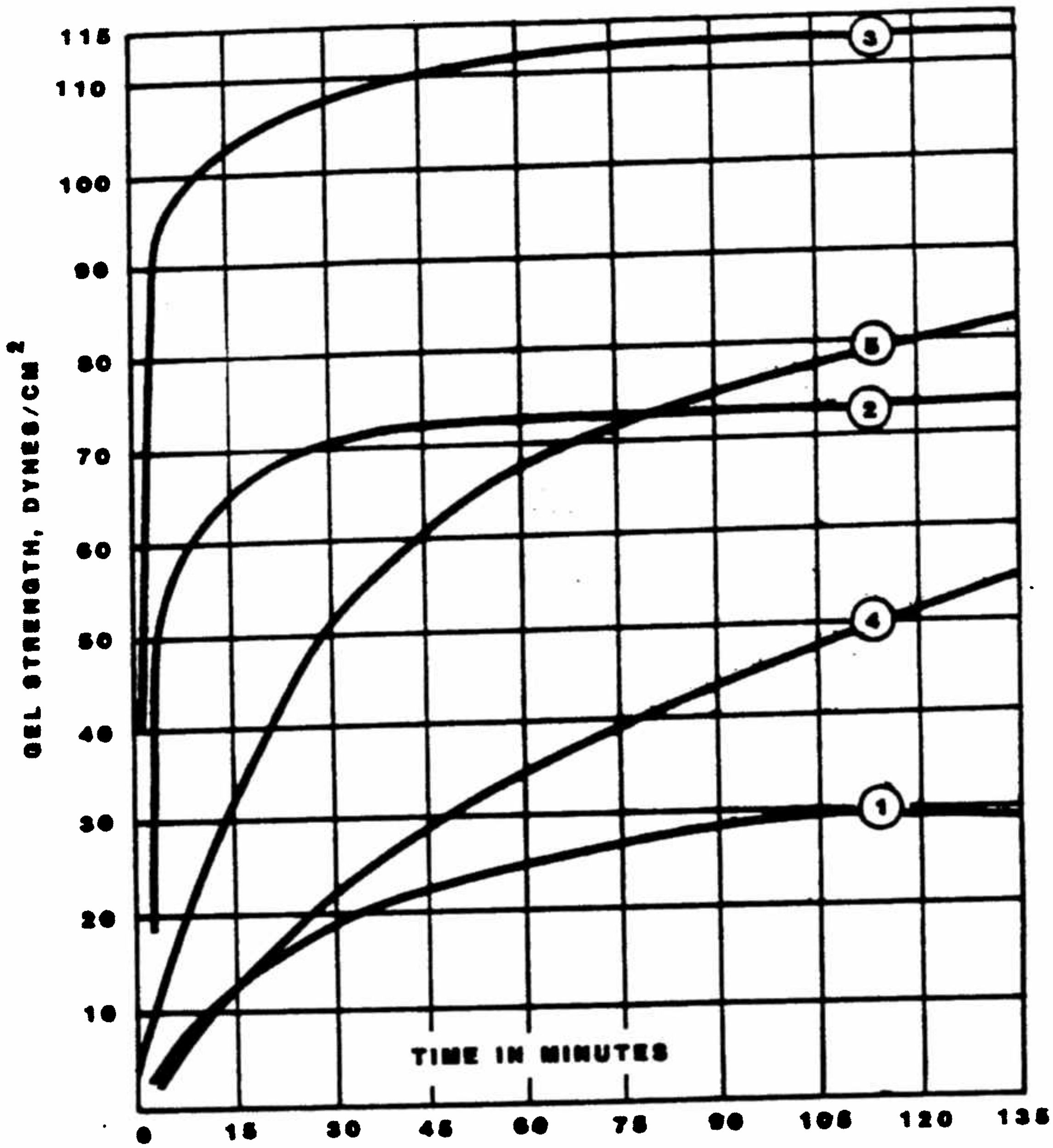


FIGURE 12

GEL STRENGTH AND RATE CONSTANTS
(FROM GARRISON 1939)
SEE TABLE 2

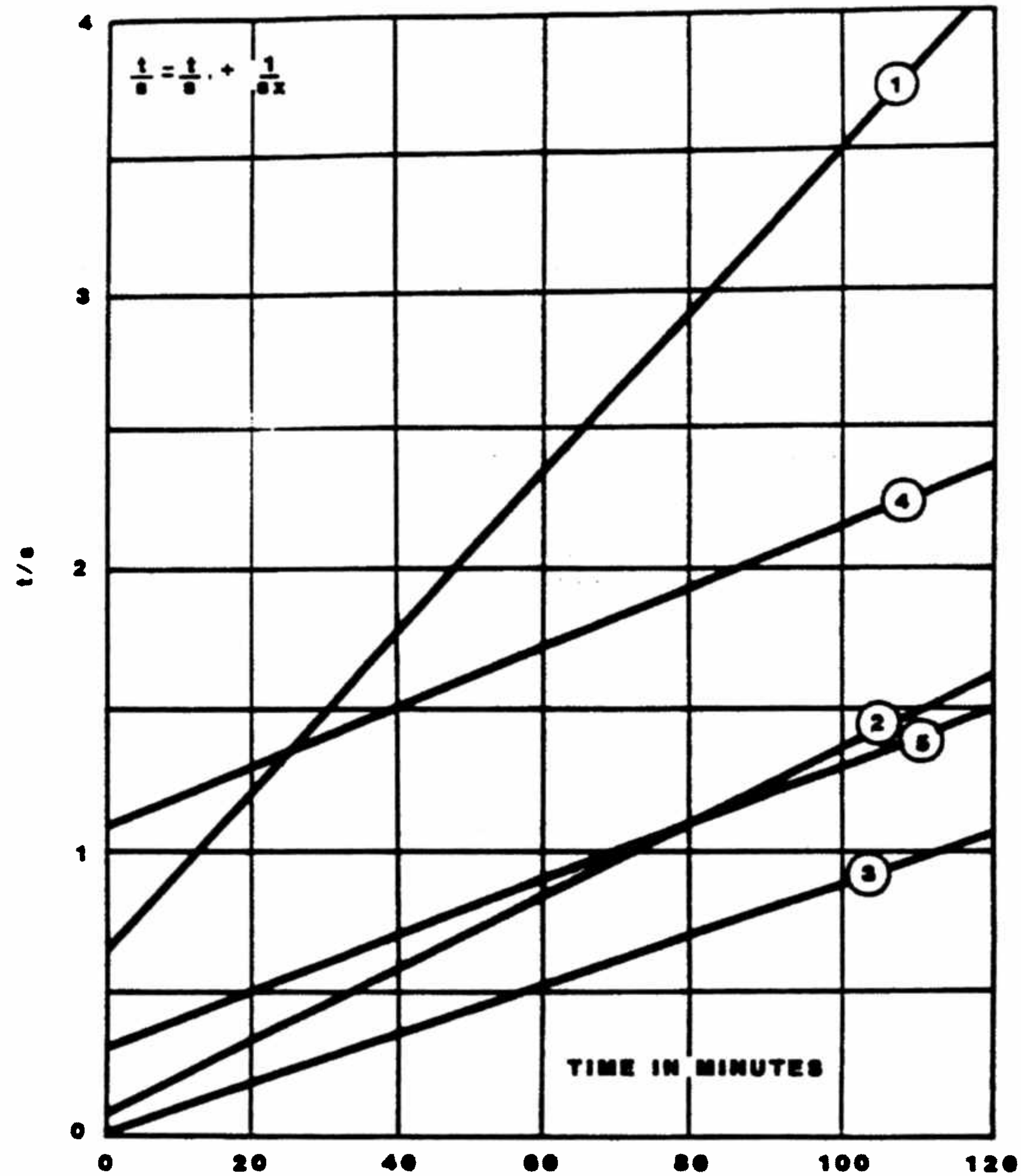


TABLE 2

GEL RATE CONSTANTS CALCULATED FROM FIGURES 11 AND 12

| Bentonite Per Cent | Sample # | Additives | Gel Strength (Ultimate) | Rate Constant |
|---|---|---|---|---|
| 4.5 | 1 | --------- | 34.4 | 0.047 |
| 5.5 | 2 | --------- | 74.4 | 0.75 |
| 6.5 | 3 | --------- | 114. | 0.79 |
| 5.5 | 4 | 0.1% Na Tannate | 104. | 0.0089 |
| 5.5 | 5 | Sodium Hydroxide | 99.7 | 0.033 |

(From Gray, Darley and Rogers)

TABLE 3

CONSTANTS IN GELLING EQUATIONS OF BENTONITE SUSPENSIONS

| Bentonite Per Cent | Gel Strength and Rate Constant | pH+ 9.2 | pH+ 9.3-9.5 | pH+ 9.9-10 | pH+ 10.8-11 |
|---|---|---|---|---|---|
| 4.5 | S′ | 34.4 | 40.1 | 48.5 | 69.6 |
| 4.5 | k | 0.047 | 0.071 | 0.076 | 0.063 |
| 5.5 | S′ | 74.4 | 32.2 | 129.9 | 152.7 |
| 5.5 | k | 0.75 | 0.22 | 0.13 | 0.18 |
| 6.5 | S′ | 114. | 141. | 250. | 268. |
| 6.5 | k | 0.79 | 0.30 | 0.10 | 0.25 |

(From Garrison 1939)

ferrochrome lignosulfonate muds for periods up to 16 hours and obtained the results presented in Table 4. They noted that although Mud E and Mud F had similar properties, Mud F developed only a moderate gel strength while that of Mud E was much greater. Once again it is observed that the initial gel strength and 10 minute gel strength measurements are not always indicative of gel strength development which is observed at elevated temperatures and extended time. The three muds designated in Table 4 were obtained from wells within the same field just prior to cementing operations.

Annis (1976) noted that when a bentonite mud is quiescent, the gelling process depends on both temperature and time. Annis compared the effect of temperature on the initial and 30 minute gel strength of an 18 ppb bentonite suspension. Figure 13 indicates that the 30 minute gel strength of the 18 ppb suspension is at any temperature approximately six times the initial gel strength. The dependence of gel strength on time at different temperatures, as noted by Annis, is shown in Figure 14. Based on these and other tests of up to 18 hours Annis concluded that there is a strong indication that gel strength increases indefinitely with time.

## Conclusion

In review, the above works indicate that the ultimate gel strength of water base muds is considerably higher than the values recorded for the initial and 10 minute gel strength. Although there is no direct relationship between gel strength and time, it is possible, based on available information, to conclude that the ultimate gel strength of a mud will be several times larger than the initial or 10 minute gel strength of the mud. In reference to the work by Garrison (1939), it is possible to consider the ultimate gel strength of a treated mud to be equivalent to that of a similar mud that was not treated, since the effect of the thinner is to decrease the rate of gelling and not the ultimate gel strength obtained.

In addition to time, temperature can have a major effect on the gel strength of water based drilling fluids. Srini-Vasan (1957) studied the effects of temperature on the gel strength of several water based drilling muds. Table 5 lists the muds which were tested and Figures 15 and 16 indicate the temperature versus gel strength relationships obtained. In most of the cases investigated by Srini-Vasan it was noted that the gel strength leveled off after 160°F. The emulsion and lime treated muds showed no change in gel strength with increase of temperature. It was found that each mud had its own characteristic curve and no quantitative interpretation was possible. The work of Weintritt and Hughes (1965) as noted in Table 4, indicates that emulsion Mud G experienced no change in gel strength in going from 75 to 180°F over a wide range of times. It is noted that although the gel strength did not vary with temperature, it went from an initial gel strength of 0 to a gel strength of 25 after 16 hours.

The equipment utilized by Srini-Vasan restricted his investigation to temperatures up to 220°F.

## TABLE 4

### COMPARISON OF MUD PROPERTIES WITH PROGRESSIVE GEL-STRENGTH TESTS GYP-FERROCHROME LIGNOSULFONATE EMULSION MUDS

| | SAMPLE | | | |
|---|---|---|---|---|
| | Mud E | Mud F | Mud G | |
| | | | No Treatment | 3 lb/bbl PCL |
| Weight, unstirred, lb/gal | 11.0 | 10.7 | 10.6 | |
| Weight, stirred, lb/gal | 11.0 | 10.3 | 10.7 | |
| Plastic Viscosity, cp | 14 | 23 | 16 | 15 |
| Yield Point, lb/100 sq ft | 3 | 6 | 2 | 1 |
| 10-sec gel, lb/100 sq ft | 1 | 2 | 1 | 0 |
| 10-min gel, lb/100 sq ft | 8 | 8 | 7 | 3 |
| API filtrate, sl | 6.2 | 3.3 | 5.2 | 2.9 |
| pH | 10.9 | 10.6 | 10.5 | 10.4 |
| Composition: water, % by vol | 76 | 63 | 75 | |
| Oil, % by vol | 5 | 11 | 9 | |
| Solids, % by vol | 19 | 16 | 16 | |
| Solids, % by wt | 39 | 36 | 37 | |
| Solids, SG | 2.7 | 2.9 | 3.0 | |
| **Filtrate Ion Analysis:** | | | | |
| **Chlorides ppm** | **3500** | **400** | **3000** | |
| **Sulfate, epm** | **250** | **300** | **130** | |
| **Carbonate, epm** | **24** | **28** | **12** | |
| **Bicarbonate, epm** | **12** | **160** | **12** | |
| **Calcium, epm** | **44** | **52** | **44** | |

| **Progressive Gel Strengths** lb/100 sq ft | **Temperature (°F)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Time** | 75° | 180° | 75° | 180° | 75° | 180° | 75° | 180° |
| 0 **minutes** | 1 | 1 | 2 | 2 | 1 | 1 | 0 | 0 |
| 3 **minutes** | 2 | 3 | 2 | 5 | 3 | 8 | 1 | 1 |
| 10 **minutes** | 8 | 18 | 8 | 12 | 7 | 26 | 3 | 3 |
| 30 **minutes** | 15 | 40 | 11 | 18 | 17 | 58 | 5 | 5 |
| 60 **minutes** | 27 | 90 | 18 | 16 | 29 | 91 | 6 | 6 |
| 2 hours | 31 | 145 | 22 | 22 | 29 | 104 | 7 | 7 |
| 4 hours | 37 | 190 | 29 | 42 | 46 | 172 | 10 | 10 |
| 8 hours | 46 | 190 | 33 | 42 | | | | |
| 16 hours | 80 | 320 | 40 | 57 | 95 | 320 | 25 | 2 |

(From Weintritt and Hughes 1965)

FIGURE 13

EFFECT OF TEMPERATURE ON INITIAL
AND 30-MINUTE GEL STRENGTH
(FROM ANNIS 1976)

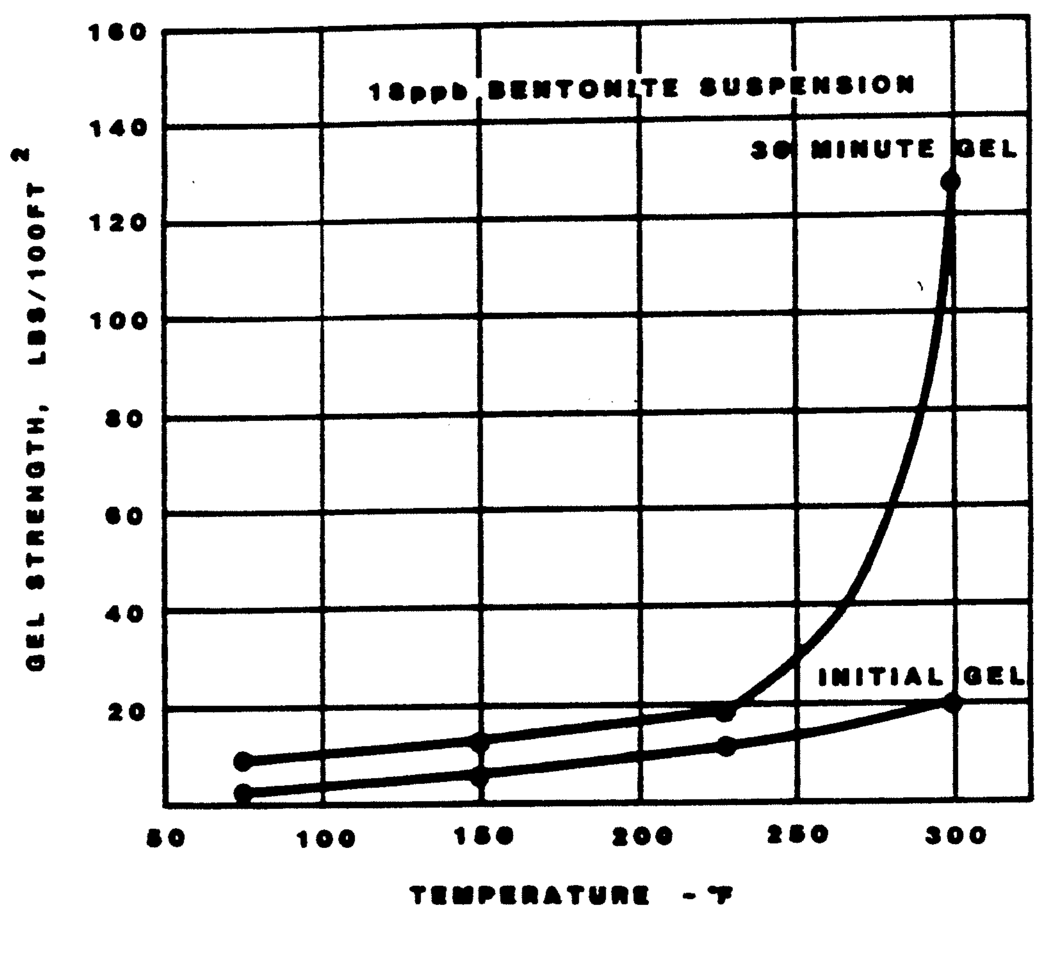


FIGURE 14
EFFECTS OF TIME AND TEMPERATURE
ON GEL STRENGTH
(FROM ANNIS 1976)

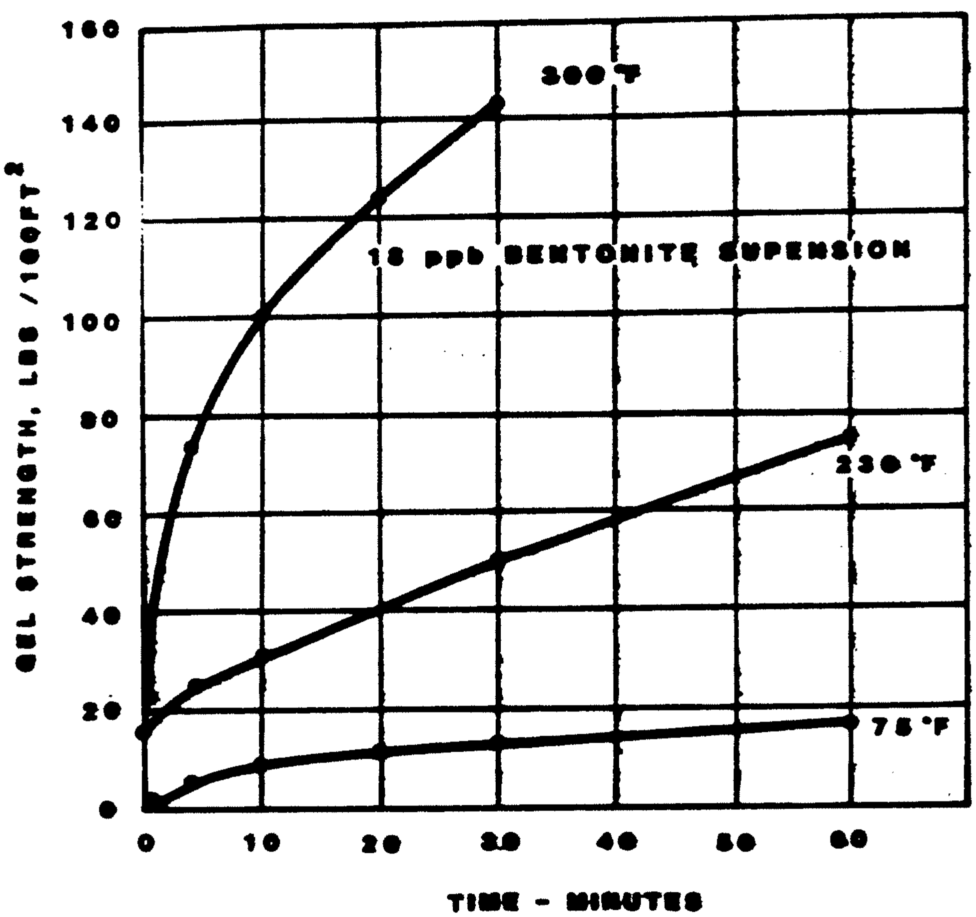


TABLE 5

COMPOSITION OF THE MUD SAMPLES TESTED FOR GEL STRENTGH

| SAMPLE NUMBER | COMPOSITION OF THE MUD** |
|---|---|
| 33 | 2 per cent bentonite mud |
| 34 | 3 per cent bentonite mud |
| 35 | 4 per cent bentonite mud |
| 39 | 10 lb/gal, 4 per cent bentonite, barite mud |
| 43 | 10 lb/gal, 10 per cent (by volume) Diesel oil, 4 percent bentonite, barite, emulsion mud |
| 47 | 10 lb/gal, 4 per cent bentonite, barite, surfactant (DMS) mud |
| 49 | 10 lb/gal, low lime (1 lb/bbl) treated, 4 per cent bentonite, barite mud |

**All muds referred to are water base muds.
All per cent quantities mentioned denote weight per cents, unless otherwise designated.

(From Srini-Vasan)

TABLE 6

GEL STRENGTH OF A 4 PERCENT SUSPENSION OF PURE SODIUM MONTMORILLONITE TO WHICH AN EXCESS OF 50 MEQ/LITER OF NaOH HAS BEEN ADDED, MEASURED AT VARIOUS TEMPERATURES AND PRESSURES

| t(°F) | P(psi) | Gel Strength (lb/100 sq ft) 1 min | 10 min | 30 min |
|---|---|---|---|---|
| 78 | 300 | 2.2 | — | 35.0 |
| | 8000 | 2.2 | — | 7.0 |
| 212 | 300 | 18.0 | 26.0 | 40.0 |
| | 8000 | 9.0 | 9.0 | 15.0 |
| 302 | 300 | 240.0 | 290.0 | 265.0 |
| | 8000 | 88.0 | 100.0 | 100.0 |

(From Hiller 1963)

FIGURE 15
GEL STRENGTH VERSUS TEMPERATURE FOR
BENTONITE-WATER MUDS (FROM SRINI-VASAN 1957)

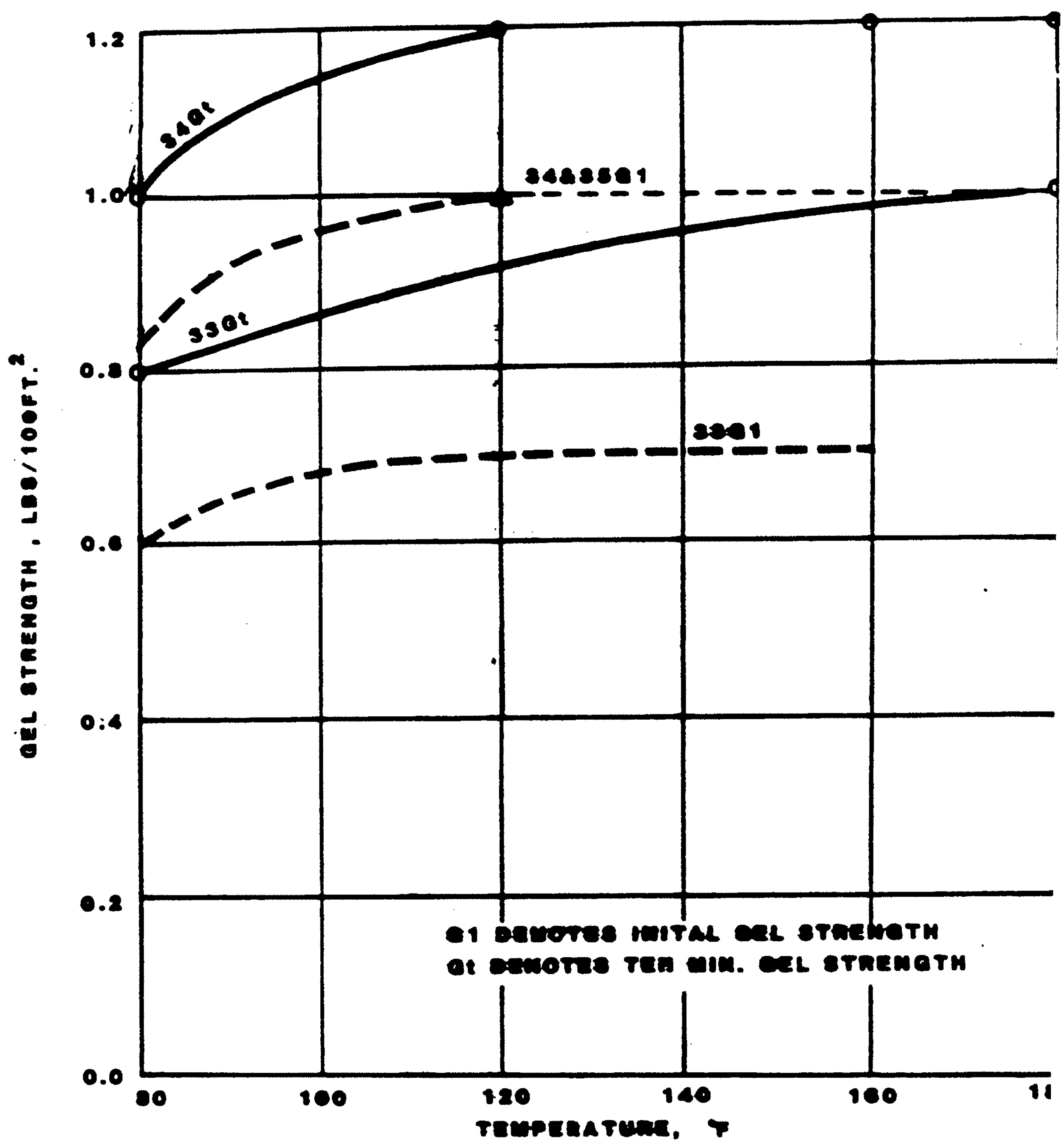
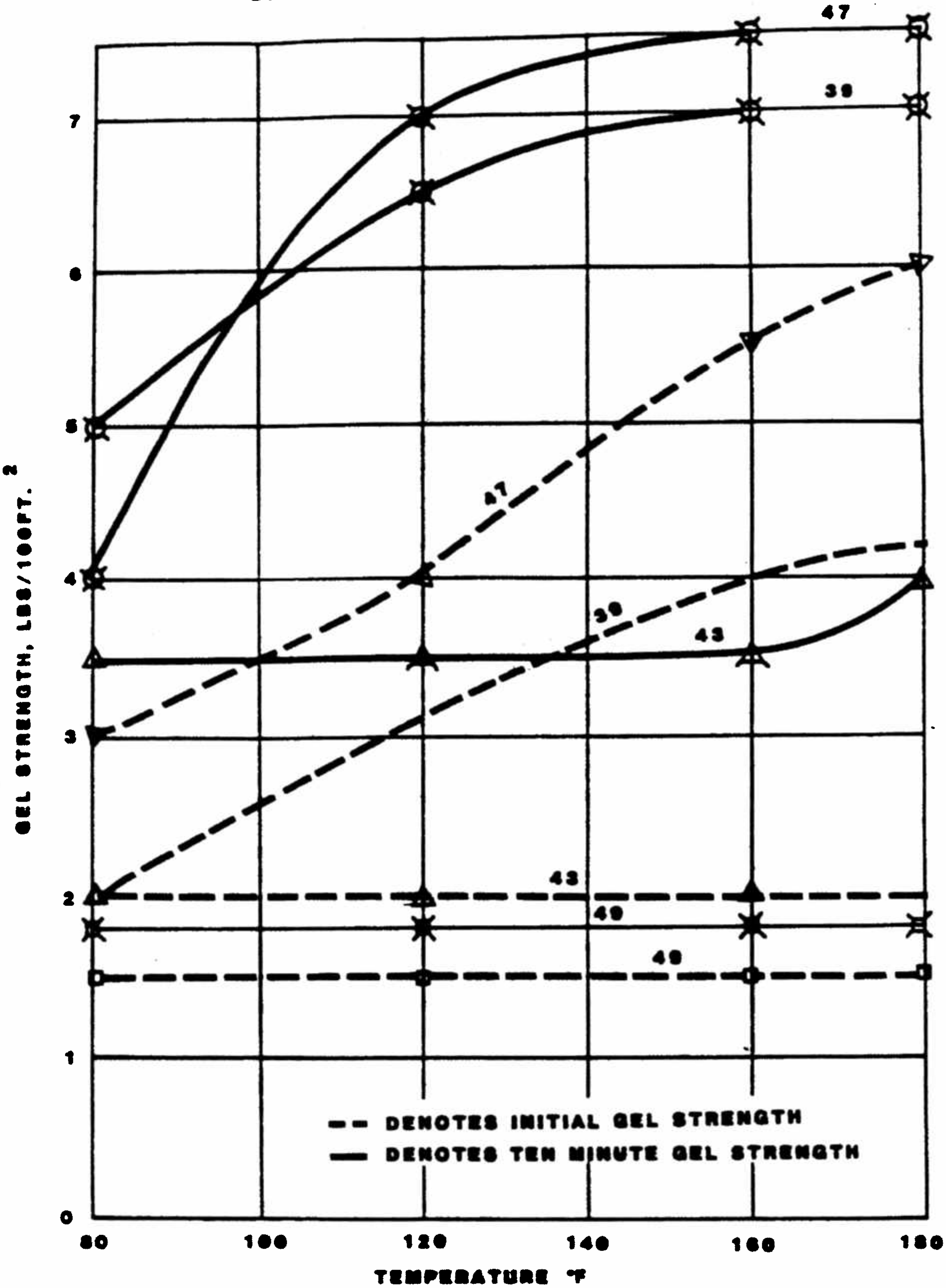


FIGURE 16

GEL STRENGTH VERSUS TEMPERATURE FOR DIFFERENT MUDS (FROM SRINI-VASAN 1957)



Annis (1976) was capable of investigating the gel strength up to temperatures of 350°F. Srini-Vasan observed that the gel strengths leveled off after 160°F but Annis noted that at higher temperature rapid increase in the gel strength was noted. Figure 17 reflects observation. Thus increased temperature, like increased bentonite concentration promotes flocculation. The temperature at which a rapid increase in gel strength occurs, represents the onset of flocculation. Therefore it is possible to expect the gel strength to increase significantly at some elevated temperature.

Annis studied the gel strength properties of about 40 water base field muds at temperatures ranging to 300°F. The muds covered a wide range of densities and mud types, although the majority were lignosulfonate muds. To draw conclusions on the effects of high temperature on gel strength, the gel strength properties were averaged and are presented in Figure 18.

Hiller (1963) noted that some clay suspensions display a decrease in gel strength with increased pressure, especially at high temperatures. It was noted that the gel strength was reduced to 1/4 of its original value for a pressure increase from 300 to 8000 psi at a temperature of 302°F. This reduction in the gel strength resulting from increased pressure is presented in Table 6.

Although no direct means exists to determine the ultimate gel strength of a drilling mud at borehole conditions, it is possible to safely say that the gel strength developed in the borehole is considerably greater than that indicated by the initial and 10 minute gel strengths recorded for a given mud. The effects of time, temperature and pressure on the gel strength of the static mud column have been discussed above. In the range of pressures and temperatures normally encountered in disposal formations, pressure should exert a negligible effect on the gel strength. Flocculation at high temperature should not occur except in the deepest of disposal formations. Certain muds do not display a temperature dependence, but the effect of time is ever present.

The research discussed above investigated muds with 0 initial gel strength to ultimate gel strengths of 100's lbs/100SF. In an attempt to select a minimum ultimate gel strength that could be expected for the worst of mud and borehole conditions, a value of 20 lbs/100 $ft^2$ should be utilized for the ultimate gel strength in all gel strength pressure calculations where actual numbers are not available. This value will provide a considerable safety factor in most cases.

The 20 lb/100 $ft^2$ ultimate gel strength was arbitrarily selected to insure that a sufficient safety factor is built into the proposed procedure. The selection is the result of individual judgment prejudiced by the above discussion."

FIGURE 17

EFFECTS OF TEMPERATURE AND BENTONITE
CONCENTRATION ON 30 MINUTE GEL STRENGTH
(FROM ANNIS 1976)

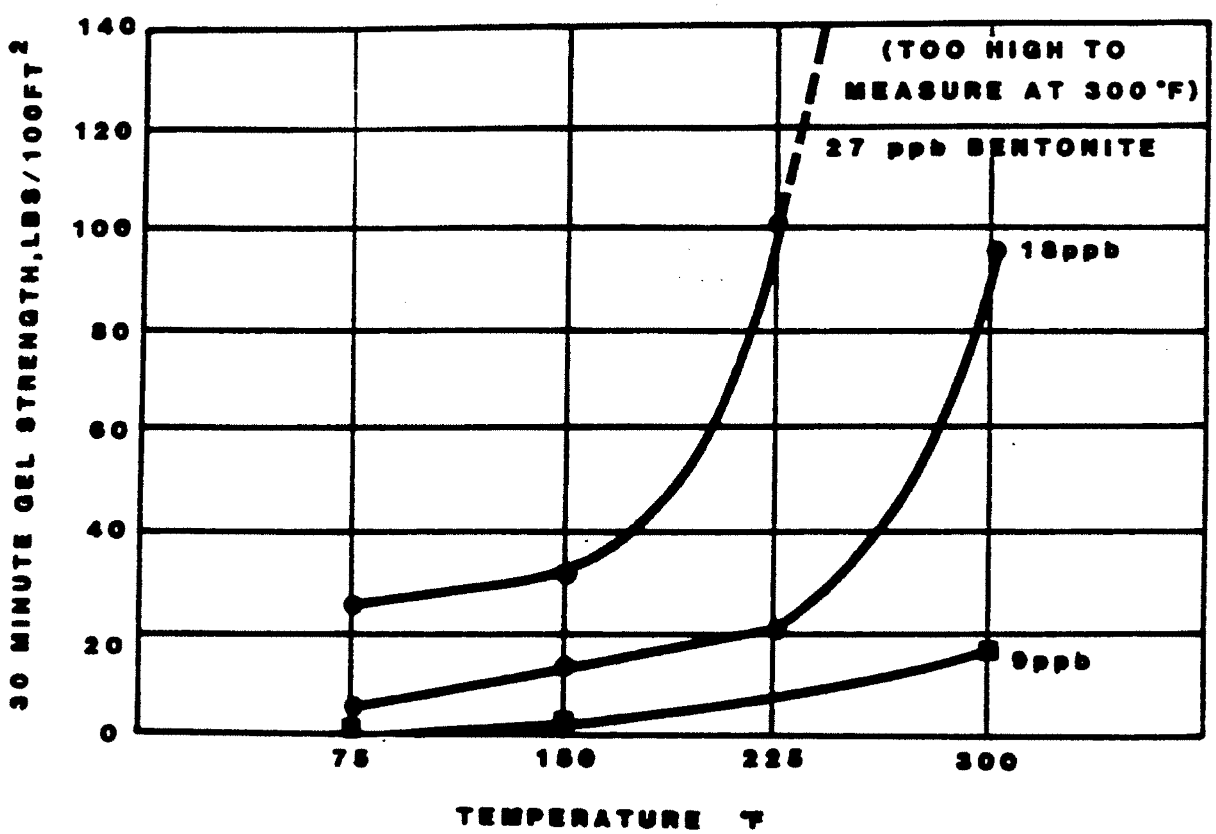
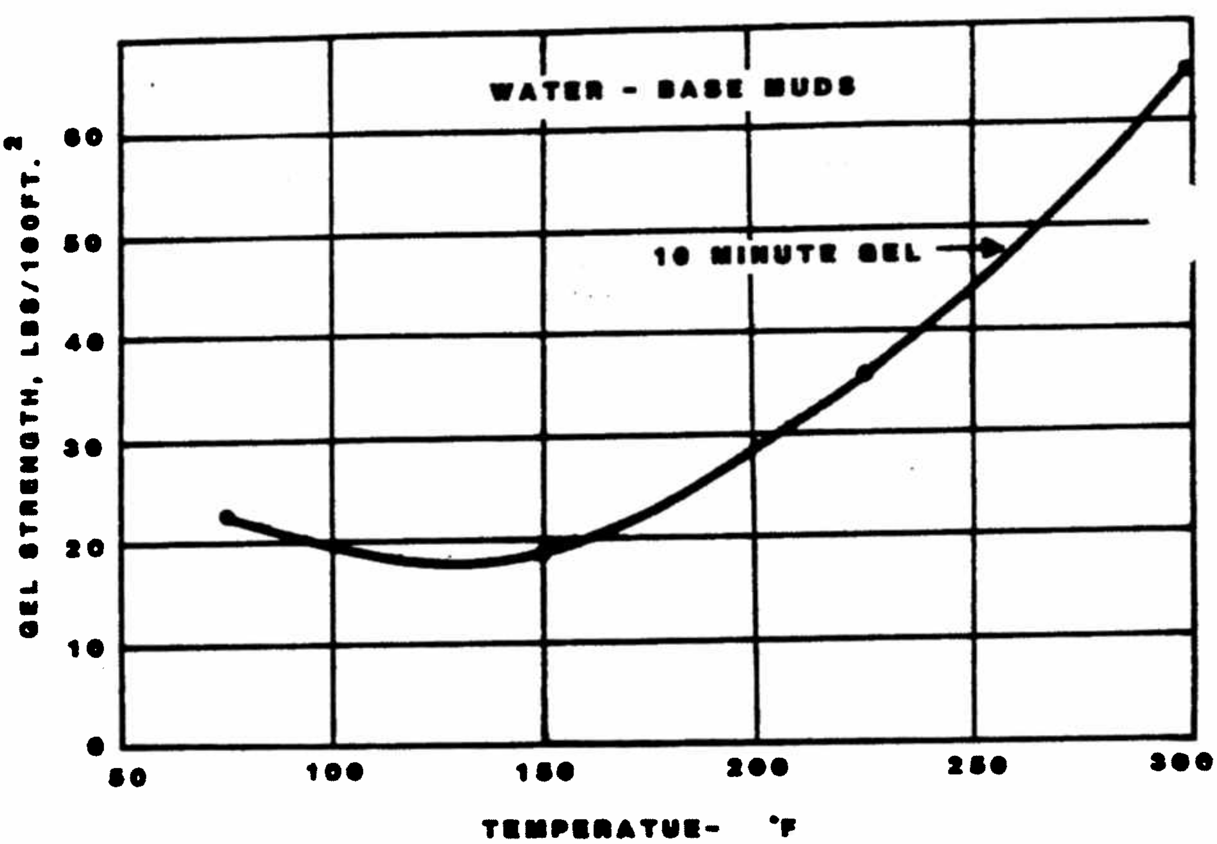


FIGURE 18

EFFECT OF TEMPERATURE ON 10 -MINUTE GEL STRENGTH (FROM ANNIS 1976)



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## About the Author

Ken E. Davis, President of Ken E. Davis Associates, 3121 San Jacinto, Suite 102, Houston, Texas 77004, has extensive experience in the field of injection well systems used for secondary recovery disposal and storage. He has either personally installed or been responsible for the installation of over fifty (50) Industrial Disposal Wells and over one hundred (100) Salt Water Disposal Wells in the continental United States, Europe and Mexico. He has also worked as technical advisor to the Environmental Protection Agency on their Underground Injection Control Program authorized by the Safe Drinking Water Act, The Department of Energy on their various Underground Storage Programs and The Bureau of Reclamation on their various salinity control projects.

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**DEQ OF LOUISIANA, 2009**

**APPENDIX 4 TO THE 2009 TRIENNIAL SUMMARY REPORT**

**IN THE EVANGELINE SUMMARY REPORT, 2007**

# EVANGELINE AQUIFER SUMMARY, 2007

## AQUIFER SAMPLING AND ASSESSMENT PROGRAM

DEQ
LOUISIANA

### APPENDIX 4 TO THE 2009 TRIENNIAL SUMMARY REPORT

PARTIAL FUNDING PROVIDED BY THE CWA

ASSET
AQUIFER SAMPLING AND ASSESSMENT PROGRAM

# Contents

# BACKGROUND

The Louisiana Department of Environmental Quality's (LDEQ) Aquifer Sampling and Assessment Program (ASSET) is an ambient monitoring program established to determine and monitor the quality of ground water produced from Louisiana's major freshwater aquifers. The ASSET Program samples approximately 200 water wells located in 14 aquifers and aquifer systems across the state. The sampling process is designed so that all fourteen aquifers and aquifer systems are monitored on a rotating basis, within a three-year period so that each well is monitored every three years.

In order to better assess the water quality of a particular aquifer, an attempt is made to sample all ASSET Program wells producing from it in a narrow time frame. To more conveniently and economically promulgate those data collected, a summary report on each aquifer is prepared separately. Collectively, these aquifer summaries will make up, in part, the ASSET Program's Triennial Summary Report for 2009.

Analytical and field data contained in this summary were collected from wells producing from the Evangeline aquifer, during the 2007 state fiscal year (July 1, 2006 - June 30, 2007). This summary will become Appendix 4 of ASSET Program Triennial Summary Report for 2009.

These data show that in January and February of 2007, and in May 2008, 12 wells were sampled which produce from the Evangeline aquifer. Eight of these 12 are classified as public supply, while there are one each classified by the Louisiana Department of Transportation and Development (LDOTD) as irrigation, industrial, domestic and other. The wells are located in 7 parishes from the central and southwest areas of the state.

Figure 4-1 shows the geographic locations of the Evangeline aquifer and the associated wells, whereas Table 4-1 lists the wells in the aquifer along with their total depths, use made of produced waters and date sampled.

Well data for registered water wells were obtained from the Louisiana Department of Transportation and Development’s Water Well Registration Data file.

# GEOLOGY

The Evangeline aquifer is comprised of unnamed Pliocene sands and the Pliocene-Miocene Blounts Creek member of the Fleming formation. The Blounts Creek consists of sands, silts, and silty clays, with some gravel and lignite. The sands of the aquifer are moderately well to well sorted and fine to medium grained with interbedded coarse sand, silt, and clay. The mapped outcrop corresponds to the outcrop of the Blounts Creek member, but downdip, the aquifer thickens and includes Pliocene sand beds that do not outcrop. The confining clays of the Castor Creek member (Burkeville aquiclude) retard the movement of water between the Evangeline and the underlying Miocene aquifer systems. The Evangeline is separated in most areas from the overlying Chicot aquifer by clay beds; in some areas the clays are missing and the upper sands of the Evangeline are in direct contact with the lower sands and gravels of the Chicot.

## HYDROGEOLOGY

Recharge to the Evangeline aquifer occurs by the direct infiltration of rainfall in interstream, upland outcrop areas and the movement of water through overlying terrace deposits, as well as leakage from other aquifers. Fresh water in the Evangeline is separated from water in stratigraphically equivalent deposits in southeast Louisiana by a saltwater ridge in the Mississippi River valley. The hydraulic conductivity of the Evangeline varies between 20 and 100 feet/day.

The maximum depths of occurrence of freshwater in the Evangeline range from 150 feet above sea level, to 2,250 feet below sea level. The range of thickness of the fresh water interval in the Evangeline is 50 to 1,900 feet. The depths of the Evangeline wells that were monitored in conjunction with the BMP range from 170 to 1,715 feet.

## PROGRAM PARAMETERS

The field parameters checked at each ASSET well sampling site and the list of conventional parameters analyzed in the laboratory are shown in Table 4-2. The inorganic (total metals) parameters analyzed in the laboratory are listed in Table 4-3. These tables also show the field and analytical results determined for each analyte. For quality control, duplicate samples were taken for each parameter at wells CU-1362 and EV-858.

In addition to the field, conventional and inorganic analytical parameters, the target analyte list includes three other categories of compounds: volatiles, semi-volatiles, and pesticides/PCBs. Due to the large number of analytes in these categories, tables were not prepared showing the analytical results for these compounds. A discussion of any detections from any of these three categories, if necessary, can be found in their respective sections. Tables 4-8, 4-9 and 4-10 list the target analytes for volatiles, semi-volatiles and pesticides/PCBs, respectively.

Tables 4-4 and 4-5 provide a statistical overview of field and conventional data, and inorganic data for the Evangeline aquifer, listing the minimum, maximum, and average results for these parameters collected in the FY 2007 sampling. Tables 4-6 and 4-7 compare these same parameter averages to historical ASSET-derived data for the Evangeline aquifer, from fiscal years 1995, 1998, 2001 and 2004.

The average values listed in the above referenced tables are determined using all valid, reported results, including non-detects. Per Departmental policy concerning statistical analysis, one-half of the detection limit (DL) is used in place of zero when non-detects are encountered. However, the minimum value is reported as less than the DL, not one-half the DL. If all values for a particular analyte are reported as non-detect, then the minimum, maximum, and average values are all reported as less than the DL. For contouring purposes, one-half the DL is also used for non-detects in the figures and charts referenced below.

Figures 4-2, 4-3, 4-4, and 4-5, respectively, represent the contoured data for pH, total dissolved solids (TDS), chloride (Cl) and iron. Charts 4-1 through 4-16 represent the trend of the graphed parameter, based on the averaged value of that parameter for each three-year reporting period.